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Determining moisture content of hay and forages using multiple frequency parallel plate capacitors

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Signatures have been redacted for privacy

DEDICATION

I would like to dedicate this work to Becky, Mom, Dad, Grandpa, and Grandma

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INTRODUCTION

Moisture content is one of the most important factors affecting the harvest, trading, storing, and handling of hay and forage. When the moisture content is too high the storage time is decreased significantly and requires the addition of certain preservatives to prevent deterioration during storage. If hay is too dry then valuable components of hay like leaves may be lost during harvest. These strict harvesting conditions require the handling of hay at the correct moisture to ensure maximum allowable storage time and decrease harvesting loss. Currently there is no quick accurate way to measure moisture content of non-compacted hay. Methods exist to determine moisture content of hay after it has been compacted. However, after the hay has been compacted it becomes extremely difficult to evenly add preservatives to the hay. Although preservatives can be added to the hay the preservatives will not be equally distributed throughout the hay. Therefore there is a need for a real time moisture sensor that will measure moisture content of hay with an unknown density prior to compaction to decrease harvest loss and maximize storage time without loss of quality.

Hay is sold on a dry weight basis, and the price will be affected by the moisture content. It could cost the buyer or seller 2 to 3 dollars per ton for each percentage point that the moisture content is incorrect. Most moisture meters are only accurate to within 2-4 percent. This is not accurate enough when buying, selling, harvesting, and storing of forages.

In Midwest states, farmers often rush baling operations to beat a rain, while in other parts of the United States baling is done at night or when there is moisture on the crop so harvesting damage is minimized. In the Midwest, farmers could get into the field quicker if they could use site-specific application of preservatives. The problems that farmers are faced with are that a thicker crop will dry slower than a thin less dense crop. Most fields have waterways that have a thick crop, and thus drying takes longer in these areas. There are other areas of the field where the crop may be less dense. The farmer must wait until the area of the field that dries the slowest is dry enough to bale so it does not spoil inside the bale, and eventually cause spoilage of the entire bale. If a farmer fears a rain, baling may be done while the hay is still very moist, leading to early spoilage. To prevent spoilage a farmer could add preservative to artificially dry the hay to keep the hay from spoiling during storage. The problem with this approach is that not all of the hay would need the preservative, and the preservative is expensive. Real time sensing of moisture could allow earlier harvesting of the hay with the addition of preservatives only when required. For the regions that must bale at night, the need to add water or remoisten the hay crop decreases the amount of harvest loss if the moisture was known.

The current moisture measuring devices are designed for compacted hay. These devices work using a probe and sticking it into the center of the bale. It only gives a moisture reading for the material that is touching the probe. The moisture content can be determined, but only with 2-4% accuracy. When the measurement is made it is too late to add the correct quantity of preservative. The density inside a bale does not have constant density, and thus the assumption that the density is constant will result in errors in the moisture measurement, therefore there is a need for research in the area of non-destructive real time moisture measurement of hay and forage.

REVIEW OF LITERATURE

Studies as early as 1940's and 1950's have been conducted on dielectric properties of grain and seeds, using a Boonton Q-meter equipped with a coaxial cylindrical test-condenser over frequency ranges of 1 to 50 hertz (Nelson et. al., 1953). Radio frequencies were some of the earliest wavelengths used to for agriculture research. Nelson and Wolf (1964) used radio frequencies to reduce the number hard seeds in alfalfa to improve germinations. The seeds were exposed to the radio frequencies for different lengths of time, and results showed a significant decrease in the number of hard seeds.

The dielectric properties of wheat were measured with a coaxial cylindrical holder connected to a RX meter at frequencies ranging from 50 to 250 MHz. The accuracy of the RX meter and the coaxial sample holder is within ± 5 percent, but could be increase with model refinement and calibration (Jorgensen et. al., 1970). Stetson and Nelson (1970) also used a coaxial cylindrical sample holder frequencies ranging from 200 to 500 MHz. Benzene and air were used to calibrate the accuracy of the test fixture, with results not better than ± 1% for dielectric constant and loss factor.

Stetson and Nelson (1972) conducted research on the dielectric properties of field corn, wheat, oats, grain sorghum, soybeans, cottonseed, alfalfa, Kentucky bluegrass, switchgrass, and Western wheatgrass in the frequencies ranging from .25 to 20 KHz. They concluded that the real permittivity decrease with increasing frequency for all samples, and the rate of change is very much dependent upon moisture content.

Nelson (1982) found that moisture content had the greatest influence on the dielectric properties of grain, although dielectric properties also vary greatly with frequency, density, temperature, kernel-size, and composition. It is known that bulk density has a large effect on the dielectric properties of grain. It is hypothesized that the same holds true for forages as well. With forages the density can change very rapidly from one material to another as well as within a particular crop.

Lawrence et al. (1993, 1998) used multiple frequencies to determine moisture content independently of density in wheat samples ranging in moisture of 11 to 22%. Stepping through frequencies in steps of 1 MHz from 1 to 10 MHz conclusions were made that the low (1 MHz) and high (10 MHz) frequencies can be used to predict moisture content of wheat. The standard deviation between predicted and oven moisture content was 0.494%.

By measuring complex impedance at two or more frequencies it is possible to determine moisture content independent of density, as well as density independently of moisture content (Zoerb et. al., 1993). The lower frequencies are better predictors of bulk density, while the higher frequencies are better predictors of moisture content (Lawrence et. al., 1998). Research by Stetson and Nelson (1972) concluded that the dielectric constant and loss factor increased linear in the range of 1 to 20 kHz as bulk density and moisture content increased. Nelson (1976) stated "However, when the dielectric properties of hard red winter wheat were measured at 9.4 GHz over a much wider range of bulk densities, the relationships between density and ε'_r and ε''_r were nonlinear and well described by quadratic equations."

Stenning and Berbert (1993) experimented with on-line moisture content measurement for grain using two frequencies, .1 and 10 MHz respectively. The test fixture was a concentric brass cylinder construction, which was believed to be a better design than the parallel plate (Stenning and Berbert 1993). Zoerb et al. (1993) showed it was possible to use rectangular plates mounted in a rectangular sheet steel pipe to measure grain moisture content during harvest. The design allowed continuous flow of grain between the plates in order to measure moisture content. This application faced many problems, one of which was the vibrations encountered in the field. The resulting prediction of the moisture content had an average standard error of 0.62 (Zoerb et. al., 1993).

Flow through a sample apparatus was designed for dynamic grain moisture measurements. The apparatus could be capped with a Teflon cap for the static samples. The standard deviation between the predicted moisture content and the standard oven moisture content was 0.36%, and the bias was 0.06% moisture content" (Lawrence et. al., 1998). The moisture content, bulk density and other factors such as geometry and dimensions of the material being tested affect the complex permittivity (Trabelsi et. al., 1999).

Research has been done on various small grains and organic materials to determine the dielectric properties for these materials. Many of these materials have a known dielectric constant at different frequencies and temperatures (Kandala et. al., 1987). However for materials such as alfalfa, brome, orchard, clover, and any combination of these materials, the dielectric constants have not been researched in great detail.

The sensing of moisture content of wheat straw was investigated using a condenser and two parallel aluminum plates 20 inches by 12 inches at frequencies ranging from 1 to 50 MHz. In order to minimize interference of exterior electrical potentials like the human body, earth, and other electric instruments, the upper positive plate was shielded with a metallic box, which was grounded to the bottom. Interactions between the dielectric properties, temperature, and humidity were minimum since temperature and humidity were closely controlled. Results indicated that at a frequency of 100KHz the moisture content was better predicted than at 1 MHz (Ko and Zoerb 1970).

An earth-plate capacitance meter constructed of 4 aluminum plates held in place with four adjustable legs was used by Angelone et al. (1980) to estimate of forage dry matter. The fixture used a rectangular plastic shield to guard the aluminum plates so fringing would be decreased. The adjustable legs allowed the aluminum plates to be raised and lowered for different crop conditions. The 4 aluminum plates could be charged separately for different readings and combinations of aluminum plate height and charge. The correlation coefficient for estimating dry weight of alfalfa, orchard grass, and tall fescue compared to standardized test were .946, .989, .950 respectively (Angelone et al., 1980).

Čech, and Poledníček (1989) researched a capacitance moisture sensor for forages constructed of flat electrodes in the shape of an annulus. The goal of the research was to develop a portable moisture tester that was timely, sufficient accurate, and real time capable of determining moisture content of forages. Their test fixture used capacitance principles, and was circular in shape with 3 different sized circular electrodes. The electrodes served to determine leakage in electric field caused by the test material. The results concluded that the sensor met the demands of the goal, and the test fixture was suitable to be used in portable forage moisture testers.

OBJECTIVES

The long-term goal of this research was to develop a moisture sensor for installation on high throughput production hay and forage equipment. In order for a parallel plate capacitor sensor to be used on hay and forage equipment, it is necessary for the sensor to be place in the flow of crop prior to the compaction stage. One area would be at the pick-up where the crop could flow between the two parallel plates. The crop flow through this region is not uniform, therefore the sensor must account for variability of crop flow through the sensing region. The material, density, and amount of material within sensor are constantly changing, and the effect that each have on the prediction capability must be determined. The specific objectives included:

1. Determine which frequencies have the greatest prediction capability for moisture content.
2. Evaluate the effect of different quantities of material within the sensor on the predictive capacity of the sensor.
3. Use two different densities to account for changes in material density and determine moisture content of the sample independent of the density of the material.
4. Evaluate different materials to determine whether crop specific or global calibration equations are required.

THEORY

Parallel Plate Capacitors

This research involved the use a parallel plate capacitor sensor for permittivity measurements from 5 hertz up to 13 megahertz. Multi-frequency sensor have been developed and used in previous research in small cereal crops, food and agricultural products. They have been tested and are proven successful. At a given frequency and temperature the complex permittivity is dependent on several factors, the largest being moisture content and bulk density. Other factors that are very important include physical properties of the material under consideration, temperature, and humidity as well as the geometric shape of the material.

Dielectric properties of interest are the complex permittivity,

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

Where the real part ε' is the dielectric constant and represents the ability of the substance to store energy, whereas the imaginary part ε'', is the loss factor and represents the loss of electric field energy in the substance, or the ability of a material to dissipate energy. For all measurements and calculations relative permittivity was used. Relative permittivity is permittivity related to free space, and calculated using equation 10.

$$\varepsilon_r = \varepsilon / \varepsilon_0 \qquad (2)$$

In general terms relative permittivity can be expressed as:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \qquad (3)$$

The impedance analyzer used in the testing gave results of complex admittance,

$$Y = G + jB \qquad (4)$$

where G the conductance, and B is the susceptance.

The dielectric constant and loss factor must be calculated from the conductance and susceptance. The susceptance is used to calculate capacitance, which can be used to determine the dielectric constant.

$$C = B / \omega \qquad (5)$$

The susceptance (B) is measured from the analyzer, and ω is the angular frequency.

$$\omega = 2 \pi f \qquad (6)$$

Using equation 7 and the capacitance the dielectric constant can be solved.

$$\varepsilon_r' = C d / \varepsilon_0 A \qquad (7)$$

Where d is the distance between the two plates, A is the area of the plates and ε_0 is defined as the permittivity of free space, and equal to 8.854×10^{-12} F/m. To calculate for the loss factor the conductance (G) must be used, and the capacitance of the empty sample holder must be calculated. The capacitance of the empty sample holder was solved for using equation 8.

$$C_0 = \varepsilon_0 A / d \qquad (8)$$

With the capacitance known the loss factor can be solved with equation 9.

$$\varepsilon_r'' = G / \omega C_0 \qquad (9)$$

Capacitors in Series

The crops were tested as a two-component mixture; material and air as shown in figure 1. Figure 1 also shows a wooden door that was used for putting material in the

Figure 1. Photograph of crop with mixture of material
and air for 50% material by volume.

fixture. The door was removed and replaced with a Rexolite plate similar to the divider plate.

Tests were run with different amounts of material in the test fixture to determine what effect the amount of air compared to the amount of material had on permittivity. In real time sensing the amount of space the material occupies and the amount of space occupied by air is unknown, so results were analyzed assuming the percentage material was unknown.

The theoretical equivalent circuit of the whole test would consist of three capacitors in series that are in parallel with two capacitors (figure 2). The three capacitors in series represent the components (air, Rexolite divider, and forage material) within the sensing chamber of the fixture. The two capacitors in parallel represent the capacitance due to the Rexolite support between the tow plates and the fringing capacitance.

The sensing chamber consist of three capacitors C_P, C_H, and C_A are in series (figure 2), where C_P is the capacitance of Rexolite divider plate, C_H is the capacitance of the material in the test fixture, and C_A is the capacitance of the air in the test fixture respectively. The equivalent capacitance, C_S of the three capacitors in series can be calculated using the following equations:

$$C_S = C_A C_H C_P / [C_A C_P + C_H C_A + C_P C_H] \quad (10)$$

In order for a parallel plate capacitor to be used on hay and forage equipment the specific quantities of C_P, C_H, and C_A would not be calculated separately, so C_S the apparent capacitance of the sample in the test fixture is used. C_M is the capacitance calculated from the measured conductance and susceptance.

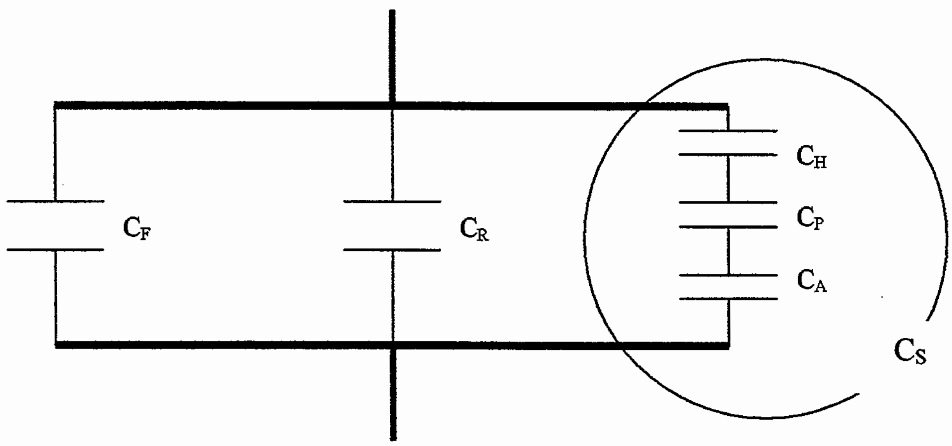

Figure 2. Capacitors in parallel and capacitors in series.

Capacitors in Parallel

The loss factor of Rexolite is known, and the fringing of the test fixture can be measured using open circuit tests so the test fixture is modeled as 3 capacitors in parallel. (Figure 2) The total equivalent capacitance C_T can be calculated from:

$$C_T = C_F + C_R + C_S \quad (11)$$

Determining Apparent ε' and ε" from B and G

Dielectric constant (ε') and the loss factor (ε") can be determined from the conductance (G) and susceptance (B) measurements from the impedance analyzer. The loss factor is calculated using the conductance. Lawrence and Nelson (1993) used similar equations for a parallel plate capacitor used to determine moisture content in wheat. The conductance measured from the impedance analyzer used in testing was total conductance. It was the sum of conductance from the Rexolite supports, fringing, and the sample as shown in equation 12.

$$G_M = G_R + G_S + G_F \quad (12)$$

G_M is the measured conductance, G_R is the conductance due to the Rexolite, G_S is the conductance of the sample material, and G_F is the conductance from fringing respectively. G_R and G_S can be written in terms of capacitance and loss factors as follows:

$$G_R = \omega\, C_0\, \varepsilon''_R \quad (13)$$

$$G_S = \omega\, C_0\, \varepsilon''_S \quad (14)$$

ω is the angular frequency equal to 2πf, with the frequency in hertz, C_0 is the capacitance of the empty sample holder in farads, ε''_R and ε''_S are the loss factors of Rexolite and the sample material respectively. Substituting G_R and G_S into equation 12 gives:

$$G_M = \omega\, C_0\, \varepsilon''_R + \omega\, C_0\, \varepsilon''_S + G_F \quad (15)$$

For the open circuit test, the test material is air, therefore the loss factor (ε_S'') is equal to zero. Therefore conductance open circuit measurement (G_{MO}) was used to determine conductance due to fringing. For the open circuit test substituting $\varepsilon_S'' = 0$ into equation 15 gives:

$$G_{MO} = \omega\ C_0\ \varepsilon''_R + G_F \quad (16)$$

The conductance due to fringing is given by:

$$G_F = G_{MO} - \omega\ C_0\ \varepsilon''_R \quad (17)$$

After solving for the conductance from fringing, equation 15 was rearranged to solve for the loss factor of the sample.

$$G_S = G_M - [G_{MO} - \omega\ C_0\ \varepsilon''_R] - \omega\ C_0\ \varepsilon''_R \quad (18)$$

$$\varepsilon_S'' = [G_M - G_{MO}]\ /\ \omega C_0 \quad (19)$$

The open circuit capacitance (C_0) is determined from the susceptance of the open circuit tests.

The dielectric constant (ε_S') can be solved using the measured susceptance. The measured susceptance can be changed to capacitance as shown in equation 20.

$$C = B\ /\ \omega \quad (20)$$

The measured capacitance (C_M) is a combination of three capacitances, the capacitance due to Rexolite supports ε'_R, fringing capacitance (C_F), and the sample capacitance (C_S). Equation 21 is used to add the three capacitances.

$$C_M = C_R + C_S + C_F \quad (21)$$

The Rexolite capacitance (C_R) and sample capacitance (C_S) can be written in terms of the dielectric constants (equation 7) as follows.

$$C_R = [\varepsilon_0 \varepsilon'_R\ A_R] / d \quad (22)$$

$$C_S = [\varepsilon_0 \varepsilon'_S\ A_S]\ /\ d \quad (23)$$

Therefore the total measured capacitance can be written as follows.

$$C_M = [\varepsilon_0\ \varepsilon'_R\ A_R + \varepsilon_0\ \varepsilon'_S\ A_S]\ /\ d + C_F \quad (24)$$

The measured capacitance (C_{MO}) for the open circuit test is as follows.

$$C_{MO} = [\varepsilon_0 \varepsilon'_R /d] A_R + [\varepsilon_0 \varepsilon'_A /d] A_S + C_F \quad (25)$$

The dielectric constant for air (ε'_A) is equal to one. Therefore the fringing capacitance can be calculated as follows.

$$C_F = C_{MO} - \varepsilon_0/d\,[A_R \varepsilon'_R + A_S] \quad (26)$$

The relationship between the measured sample capacitance C_M and the sample dielectric constant (ε'_S) can be determined from equation 24 and 26 as follows.

$$C_M - C_{MO} = \varepsilon_0 A_S /d\,[\varepsilon'_S - 1] \quad (27)$$

Therefore the dielectric constant is given by:

$$\varepsilon'_S = 1 + [d / \varepsilon_0 A_S]\,[C_M - C_{MO}] \quad (28)$$

Using the relationship $C = B/\omega$ the dielectric constant is determined from the measured susceptance (B_M) as follows.

$$\varepsilon'_S = 1 + [d / \varepsilon_0 A_S \omega]\,[B_M - B_{MO}] \quad (29)$$

Where A_S = the area of the sample material and B_{MO} is the susceptance measured for the open circuit test (Lawrence and Nelson 1993).

MATERIAL AND METHODS

Impedance Test Apparatus

The tests were conducted using a HP 4192A LF Impedance Analyzer with a frequency range from 5 hertz to 13 megahertz coupled with a 16095A probe fixture. A HP Pentium computer programmed with Q-Basic code controlled the impedance analyzer, via a HP-IB GPIB 32 computer board. A parallel plate test fixture that the HP Impedance Analyzer was connected to was constructed from aluminum and Rexolite 1422. Four aluminum plates were used, one of which was connected to the positive pin on the BNC connector while an aluminum strip grounded the 3 other aluminum plates (figure 3). Rexolite 1422 support members was the used in the experiment because of its excellent dielectric constant over a large range of frequencies. The Rexolite was used as support members on the sides as well as a movable divider so the different material to total volume percentages could be ran. An engineering drawing with dimensions is shown in figure 4.

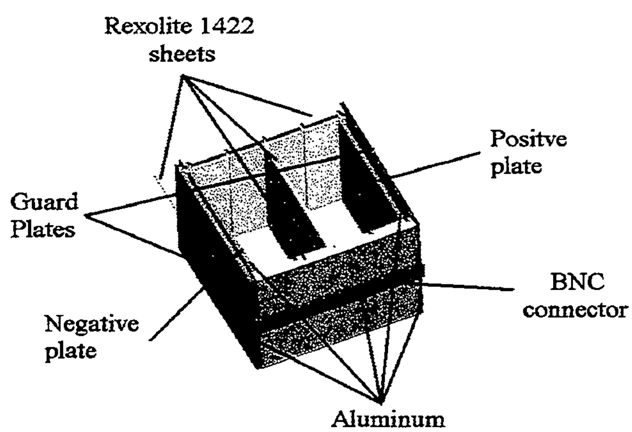

Figure 3. Cad drawing show parallel plate capacitor test fixture.

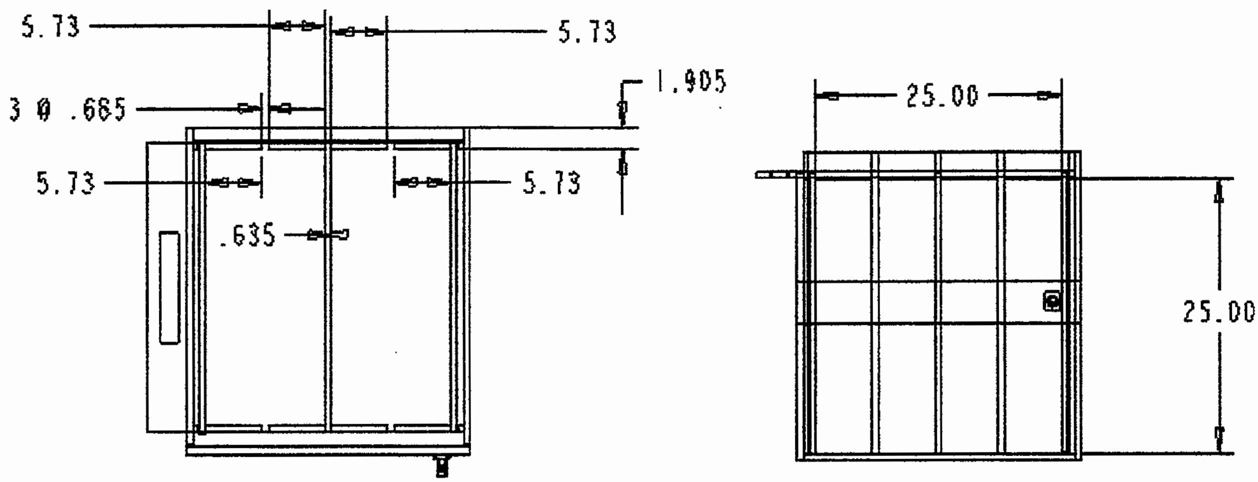

Figure 4. Cad drawing of test fixture with dimensions.

Gathering of Materials

Four different crops and two different mixtures were gathered. Alfalfa, clover, brome, orchard, as well as brome-clover, and brome-alfalfa mixtures were collected. Forages were taken from the Iowa State University Agronomy Department's forage plots. Plots were pure stands of alfalfa, clover, brome grass, and orchard grass respectively, while mixtures of were 50 percent legume, 50 percent grass. All samples were first cutting, gathering took place during mid-day so exterior moisture would not affect testing. Each crop was mowed one at a time with a sickle bar mower at low speed as shown in figure 5. Samples were raked together with lawn rakes, and loaded by hand then transported to a controlled environment by truck with an enclosure.

Preparation of Materials

Each sample was spread out evenly on an individual piece of plastic, and labeled. Crops were given ample room for drying as shown if figure 6, and room temperature was held between 65 and 72 degrees, while the relative humidity was held between 35 and 41 respectively. Cardboard was placed over windows to block the sun from shining on crops, and drying them uneven. Every 12 hours the crops were mixed, and turned for more equal drying.

Figure 5. Photograph of sickle mower cutting alfalfa.

Figure 6. Photograph of sample drying in the lab.

Testing Sequence

Samples were randomly taken from each material, and tested one crop at a time. A random sample was gathered, weighted to the nearest tenth with an Ohaus model GT8000 scale with digital readout, and placed in the testing fixture starting with the 25% full test. Crop filled 25% of the fixture with the other 75% occupied with air at room temperature and humidity. The temperature and humidity were measured with a Fisher Scientific sensor with an accuracy of ±1.5 % for relative humidity, and ± .4°F for temperature. The test of complex permittivity was started, while the test being performed another sample was weighted. Samples weights were based on moisture content and desired density. Masses were determined based on a dry weight sample. The nominal mass of dry material in the test fixture was held constant for all tests. The change in total mass in the test fixture is a result of the change in moisture content of the material only. Crops were tested at approximately 80, 40, 20, and 10% moisture content respectively. The masses and moisture contents of the tests can be seen in Table 1.

In order to reach these moisture content, drying times shown in Table 2 were used. When the first test was completed the weighed sample was placed in the fixture, and the test was repeated. The same steps were followed until a complete set of three replications at two different densities; four moisture contents, and three material to total volume percentages were completed on all six crops. In order to get an estimate of the moisture content of the material while testing a rapid approximate moisture determination method was used. This method used a microwave of at least 600 watts at full power for three-minute intervals until the change in moisture content is less than 1% during each interval.

Table 1. Amount of material (grams) in test fixture at each moisture content and percentage material by volume.

Material Volume % of Fixture	Density	MASS OF MATERIAL IN TEST FIXTURE[1] MOISTURE CONTENT[2] 80%	40%	20%	10%
25	Low	200	60	50	45
	High	400	120	100	90
50	Low	400	120	100	90
	High	800	240	200	180
100	Low	800	240	200	180
	High	1600	480	400	360

1. Mass selected to maintain approximately equal mass of dry matter for all moisture contents at the two densities.
2. Nominal moisture content of forage on wet basis.

Table 2. Testing Times of the 6 different materials.

Material	TIME OF TEST SEQUENCE (hours). MOISTURE CONTENT[1] 80%	40%	20%	10%
Alfalfa	0	48	94	166
Clover	0	49	93	141
Brome	0	44	96	144
Orchard	0	40	88	138
Brome/Alfalfa	0	46	96	144
Brome/Clover	0	47	96	143

1. Nominal moisture content of forage on wet basis.

During the testing a separate sample was taken for each test and placed in a 4-inch diameter by 3-inch high tin for the standardized oven-drying test. The tins were weighted with a Denver Instrument DI-4K digital scale with readout accuracy to the nearest hundredth, and then the samples were dried in a VWR Scientific Inc. oven. The standardized moisture content was calculated on a wet basis according to ASAE standard S358.2. This standard has two oven-drying moisture determination methods, one of which is for moisture only where material is placed in the oven for 24 hours at 103°C. The other method is used for chemical analysis where the material is placed in the oven for 72 hours at 60°C. The second method was used for this research so chemical analysis could be done as well as moisture content determination. Equation 10 was used for the standardized calculations of moisture content.

MC (wb%) = loss in weight * 100/ weight of wet sample ....(22)

Where MC is the moisture content, and wb is wet basis (ASAE Standard S358.2 1994).

Statistical Analysis

Random samples were tested at four moisture contents. A material samples were randomly selected and were placed in the test fixture starting with the 25% forage to total volume, and low density. The second test was the high-density test at the 25% material volume. Another sample was gathered and the test was repeated at the 50% and 100% forage to total volume respectively. Separate samples were placed in tins for standardized moisture content measurements.

Results were placed in a spreadsheet and imported into the statistical program SAS, where stepwise linear regression was used to predict moisture content. Linear stepwise regression analysis used moisture content as the dependent variable and the conductance and the susceptance over frequency ranges of 5 Hz to 13 MHz as the independent variables. The best prediction models from the stepwise linear regression models were used to determine the predicted moisture content for each sample. The prediction error was determined, and linear regression was used to find the root mean square error of each material at each particular percentage material. The effect of density and the percentage material in the test fixture had on prediction of moisture content was evaluated using the GLM procedure of SAS.

RESULTS AND DISCUSSION

Determination of Optimum Frequencies for Moisture Content Prediction

Stepwise linear regression was performed on all the data to determine the best prediction models. The data was sorted by material and modeled with moisture content as the dependent variable, and conductance and susceptance as the independent variables. Stepwise linear regression increased the number of factors in the model until no other variable met the 0.1500 significance level for entry into the model. The frequencies that were used in the prediction model as shown in Table 3. In all the prediction equations, frequencies of 900 KHz or above were included in the model with the exception of 5 Hz frequency included in the clover prediction model. The prediction of moisture content in grasses used 4 or less factors in the prediction model while legumes used 6 or more. Moisture content prediction of grass/legume mixtures used 4 and 6 factors respectively.

The r^2 for the number of factors in the prediction for each different material, and all materials together is shown in table 4. The best prediction models for the two legumes alfalfa and clover included 4 and 6 factors with a correlation coefficient of 0.95 and 0.90 respectively. Prediction models for the two grasses brome and orchard used 3 and 4 factors and the correlation coefficients were only 0.78 and 0.74. The mixtures brome/alfalfa and brome/clover had a wide range of moisture content prediction. The moisture content prediction model for brome/alfalfa used 3 factors, and had the worst resulting correlation coefficient of 0.65. Brome/clover used 7 factors in the prediction model, with a correlation coefficient of 0.94.

Table 3. Frequencies used in model of moisture content prediction for each material.

	Number of Factors	r^2	Frequencies Included in Prediction Model[1,2] (Hz)						
LEGUMES									
Alfalfa	1	.22	$10M_B^{***}$						
	2	.72	$10M_B^{***}$	$13M_G^{***}$					
	3	.78	$10M_B^{**}$	$13M_G^{***}$	$5M_B^{***}$				
	4	.85	$10M_B^{***}$	$11M_G^{***}$	$5M_B^{***}$	$9M_B^{***}$			
	5	.95	$900K_G^{***}$	$9M_G^{***}$	$5M_B^{***}$	$12M_G^{***}$	$9M_B^{***}$		
	6	.95	$900K_G^{***}$	$9M_G^{***}$	$5M_B^{***}$	$9M_B^{***}$	$12M_G^{***}$	$11M_G$	
	7	.95	$900K_G^{***}$	$9M_G^{***}$	$5M_B^{***}$	$9M_B^{***}$	$12M_G^{**}$	$13M_G$	$11M_G$
Clover	1	.21	$10M_B^{***}$						
	2	.60	$10M_B^{***}$	$13M_G^{***}$					
	3	.80	$10M_B^{***}$	$13M_G^{***}$	$5M_B^{***}$				
	4	.82	$13M_G^{***}$	5_B^{***}	$5M_B^{***}$	$10M_B^{***}$			
	5	.90	$10M_G^{***}$	5_B^{***}	$5M_B^{***}$	$6M_B^{***}$	$10M_B^{***}$		
	6	.91	$10M_G^{***}$	5_B^{***}	$5M_B^{***}$	$6M_B^{***}$	$10M_B^{***}$	$13M_B^{***}$	
GRASSES									
Brome	1	.22	$13M_B^{***}$						
	2	.72	$9M_B^{***}$	$10M_B^{***}$					
	3	.79	$9M_B^{***}$	$10M_B^{***}$	$11M_B^{***}$				
	4	.73	$9M_B^{***}$	$10M_B^{***}$	$13M_G$	$12M_B$			
Orchard	1	.24	$13M_B^{***}$						
	2	.63	$13M_B^{***}$	$13M_G^{***}$					
	3	.74	$13M_B^{***}$	$13M_G^{***}$	$12M_G^{***}$				
MIXTURES									
Brome/alfalfa	1	.19	$11M_B^{***}$						
	2	.57	$11M_B^{***}$	$10M_B^{***}$					
	3	.65	$11M_B^{***}$	$9M_B^{***}$	$13M_B^{***}$				
	4	.65	$11M_B^{***}$	$10M_B$	$9M_B^{**}$	$13M_B^{***}$			
Brome/Clover	1	.23	$11M_B^{***}$						
	2	.54	$11M_B^{***}$	$9M_B^{***}$					
	3	.60	$11M_B^{***}$	$10M_B^{***}$	$9M_B^{***}$				
	4	.74	$13M_B^{***}$	$11M_B^{***}$	$10M_B^{***}$	$9M_B^{***}$			
	5	.88	$7M_B^{***}$	$9M_B^{***}$	$10M_B^{***}$	$12M_B^{***}$	$13M_B^{***}$		
	6	.93	$3M_G^{***}$	$7M_B^{***}$	$8M_B^{***}$	$10M_B^{***}$	$12M_B^{***}$	$13M_B^{***}$	
	7	.94	$300K_B^{***}$	$3M_G^{***}$	$7M_B^{***}$	$8M_B^{***}$	$10M_B^{***}$	$12M_B^{***}$	$13M_B^{***}$

[1] The subscripts G and B signify conductance or susceptance respectively.
[2] Symbols ***, **, * represent 1%, 5% and 10% respectively.

Table 4. Correlation coefficients between the numbers of factors in model for each forage type.

	Correlation Coefficient (r^2)							
	Number of Factors in Model							
Material	1	2	3	4	5	6	7	12
All material	0.1984	0.4343	0.5450	0.5842	0.6235	0.6439	0.6709	0.7512†
Alfalfa	0.2249	0.7163	0.7758	0.8538	0.9532†	0.9527	0.9527	
Brome/Alfalfa	0.1891	0.5656	0.6474†	0.6474				
Brome/Clover	0.2303	0.5420	0.5955	0.7429	0.8834	0.9296	0.9434†	
Brome	0.2211	0.7211	0.7845†	0.7284				
Clover	0.2138	0.5949	0.8030	0.8218	0.8979	0.9092†		
Orchard	0.2381	0.6263	0.7411†					

† Symbol signifies best prediction model.

Evaluation of Material Volume on Moisture Content Prediction

The root mean square error, and correlation coefficient for the different amounts of material within the test fixture are shown in figures 7 and 8. There is no trend for the amount of material in the test fixture to have an effect on the predictive capability of the sensor, although the graphs do show that the sensor is specific to crop. Graphs of actual vs. predicted moisture content for the different materials tested are shown in figures 9-14, where the different symbols represent the different amount of material in the fixture. These results are summarized in table 5.

The predictive capability of the system was greatest for alfalfa (figure 9). The RMSE for alfalfa was 4.99 when all test were included in the model. The RMSE for the 25%, 50%, and 100% tests of alfalfa were 4.88, 4,87, and 5.09 respectively. The slope of the linear regression line ranged from 0.90 to 1.00, and the correlation coefficient had a range from 0.95 to 0.96.

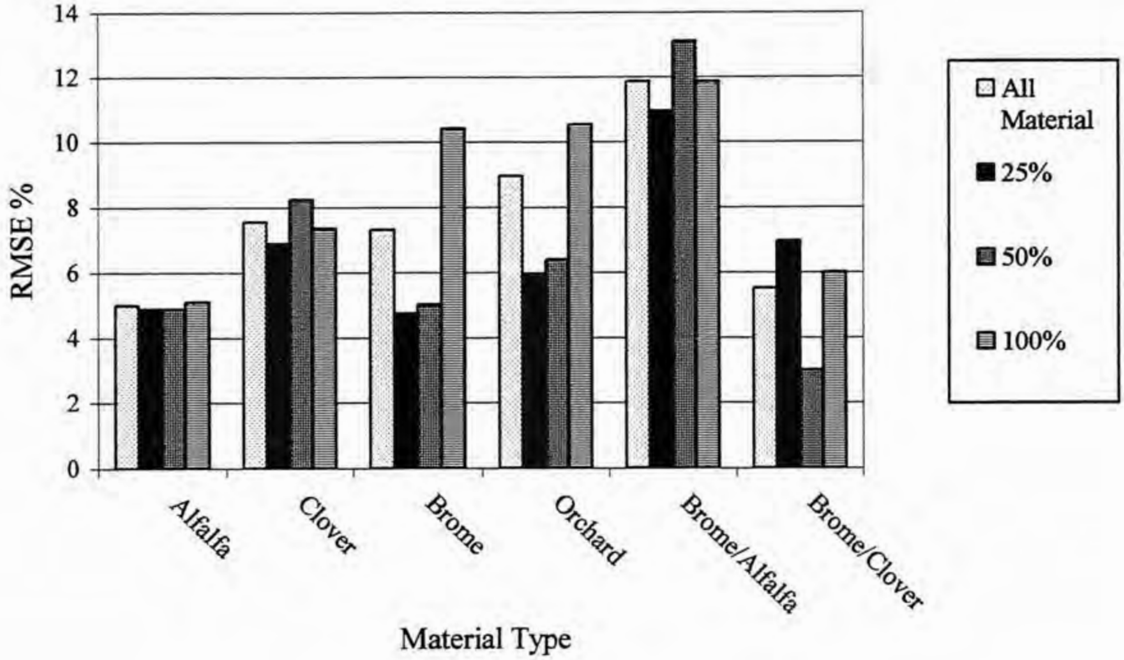

Figure 7. RMSE for all six crops tested, for different volume of material tested in the test fixture.

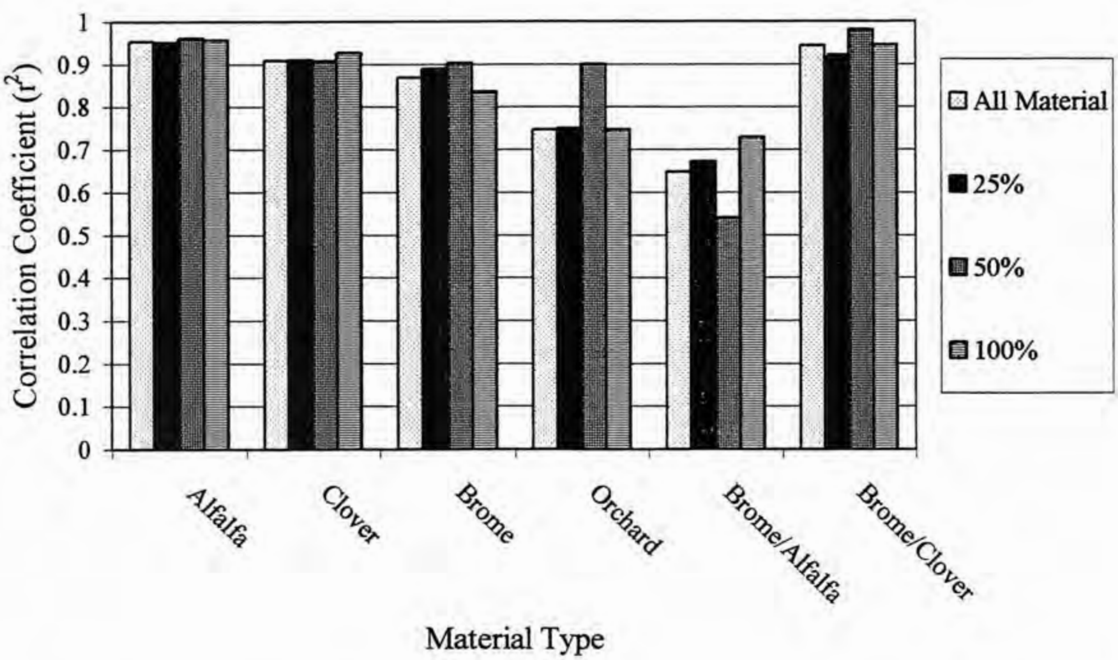

Figure 8. Correlation Coefficient for all six crops tested, for different volume of material tested in the test fixture.

The prediction model fits the data, and the moisture content is not dependent on the amount of material in the test fixture.

Figure 10 shows the other legume, clover, which had RMSE results of 7.55 for all clover data. The RMSE for each different percentages of material in the fixture were 6.89, 8.23, and 7.36 for the 25%, 50%, and 100% tests. The correlation coefficients were slightly lower than alfalfa. The correlation coefficients were still much higher than the grasses, which were 0.91 for all clover, 0.91 for 25% clover, 0.90 for 50% clover, and 0.93 for 100% clover. These data shows that the amount of clover in the test fixture does not effect the moisture content prediction.

The prediction error was greater for the grasses, brome and orchard (figures 11 and 12). The RMSE was 7.31 and 8.97 for all test for the brome and orchard samples. The slopes of the regression equations ranged from 0.63 to 0.77 for brome, and 0.48 to 0.89 for orchard. The correlation coefficients for brome were 0.87 for all brome, 0.89 for the 25% brome, 0.90 for the 50% brome, and 0.83 for the 100% brome tests. Orchard had correlation coefficients of 0.75 for all orchard data, 0.75 for the 25% orchard, 0.90 for the 50% orchard, and 0.75 for the 100% orchard.

The mixtures of grasses and legumes (figures 13 and 14) gave mixed results, with brome/clover results were similar to the legumes, and brome/alfalfa results were worse than the grasses. The RMSE for all brome/clover data was 5.51. The RMSE for the 25%, 50%, and 100% test were 6.97, 2.99, and 6.00 respectively. The slopes of the regression equations ranged from 0.92 to 1.00 for the brome/clover data. The correlation coefficient for all brome/clover data was 0.94. The 25% material test had a correlation coefficient of 0.92, while the 50% was 0.98, and 100% was 0.94 respectively.

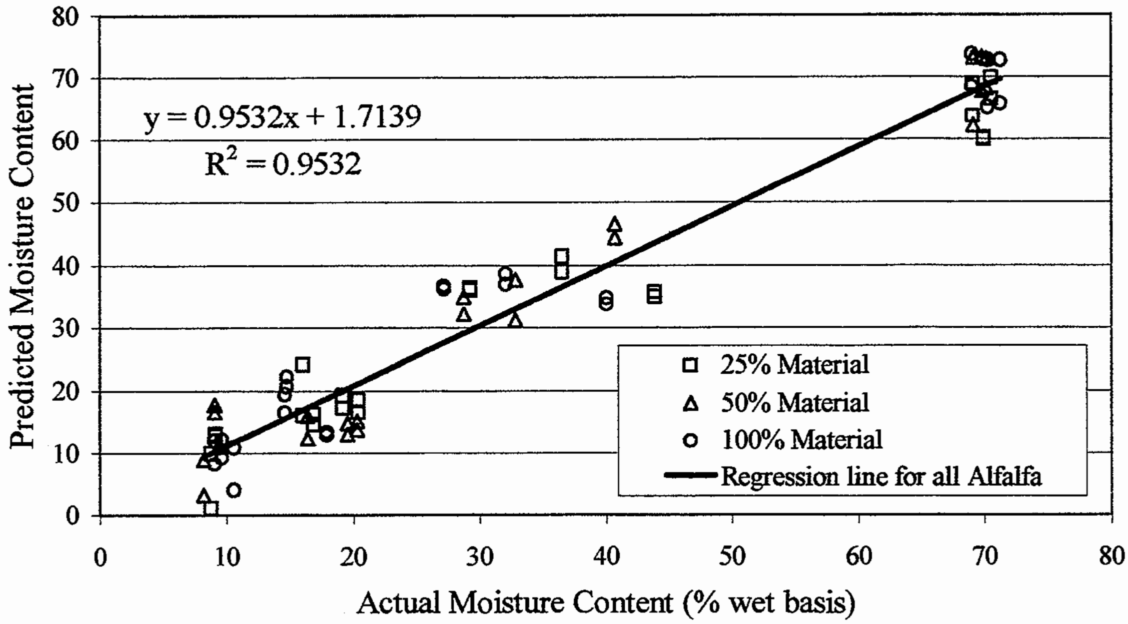

Figure 9. Regression line of actual moisture content vs. predicted moisture content for all alfalfa data. Different symbols are used to represent different volumes of material in the fixture.

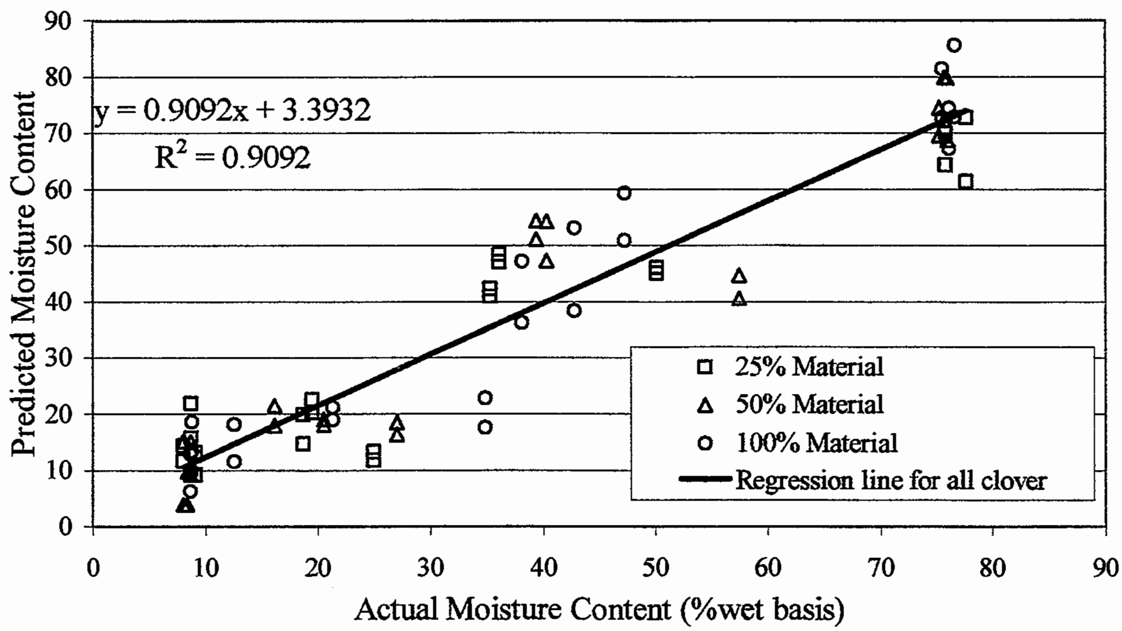

Figure 10. Regression line of actual moisture content vs. predicted moisture content for all clover data. Different symbols are used to represent different volumes of material in the fixture.

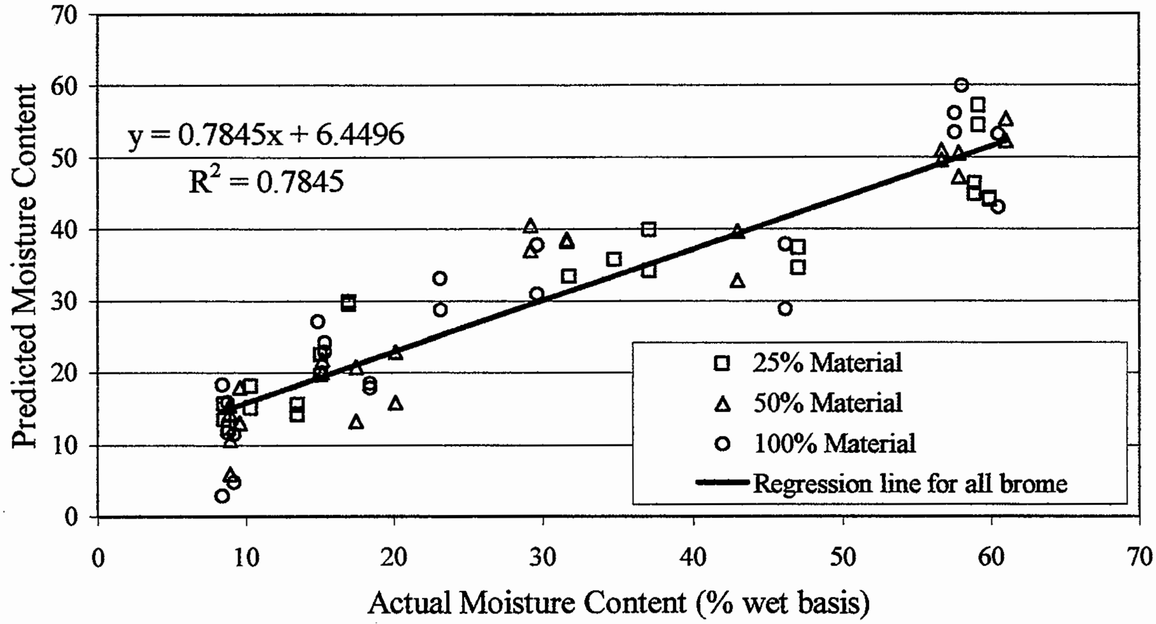

Figure 11. Regression line of actual moisture content vs. predicted moisture content for all brome data. Different symbols are used to represent different volumes of material in the fixture.

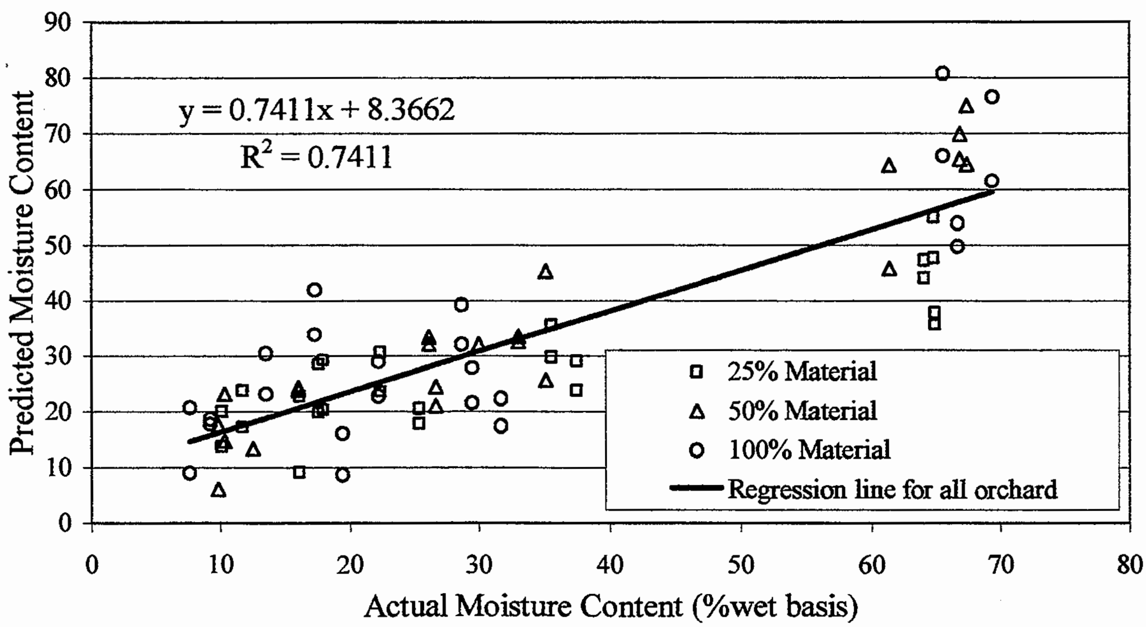

Figure 12. Regression line of actual moisture content vs. predicted moisture content for all orchard data. Different symbols are used to represent different volume of material in the fixture.

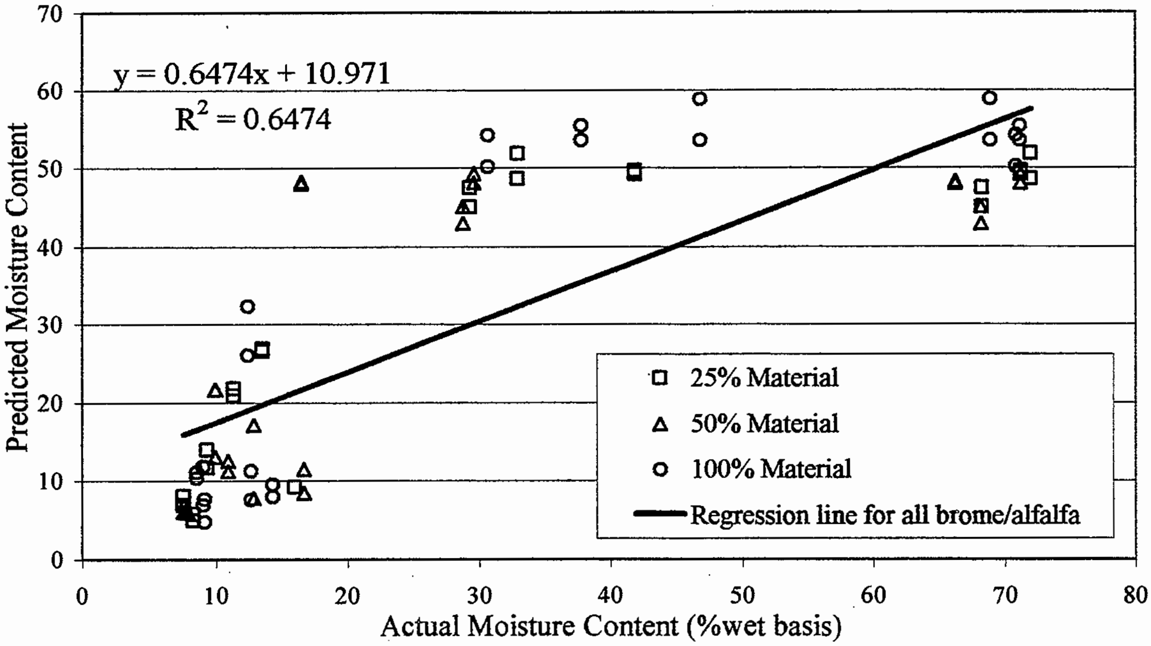

Figure 13. Regression line of actual moisture content vs. predicted moisture content for all brome/alfalfa data. Different symbols are used to represent different volumes of material in the fixture.

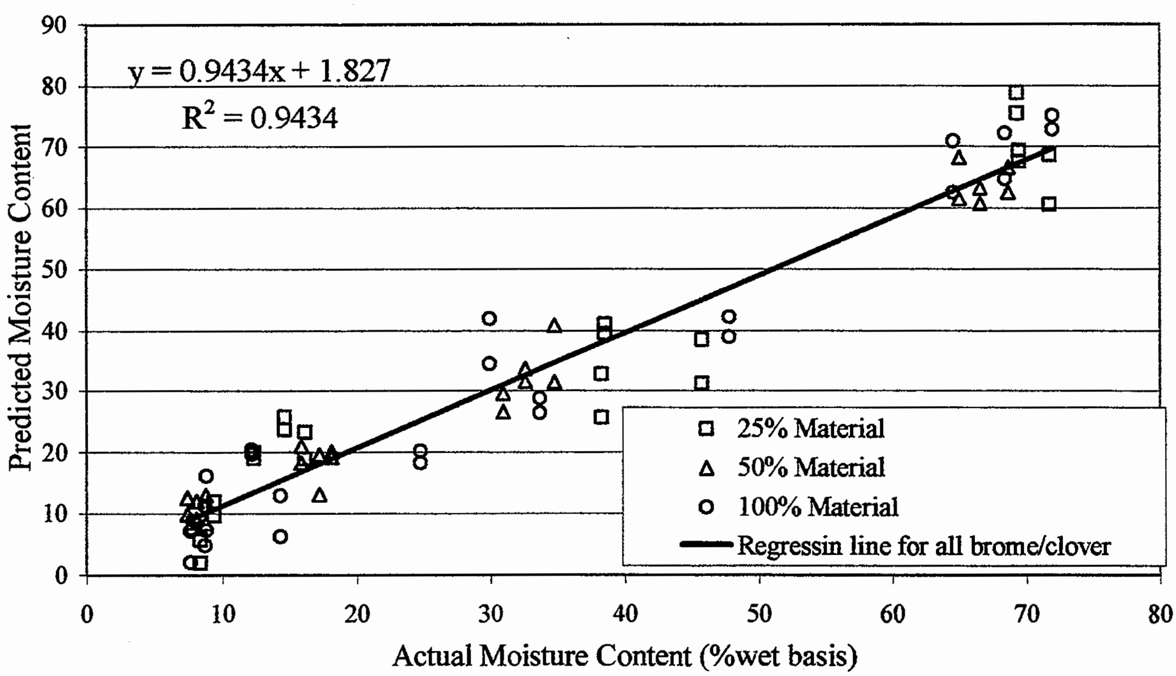

Figure 14. Regression line of actual moisture content vs. predicted moisture content for all brome/clover data. Different symbols are used to represent different volumes of material in the fixture.

Table 5. Regression equations for prediction vs. actual moisture content.

Material		Linear Regression equation			
		r-squared	Slope	Intercept	RMSE[1]
LEGUMES	Alfalfa (all material)[2]	.9532	.9532	1.714	4.99
	Alfalfa (25% material)	.9505	.8958	2.495	4.88
	Alfalfa (50 %material)	.9614	1.0014	.412	4.87
	Alfalfa (100 % material)	.9566	.9638	2.266	5.09
	Alfalfa (low density)[3]	.9521	.9186	2.314	4.94
	Alfalfa (high density)	.9574	.9877	1.113	4.99
	Clover (all material)	.9092	.9092	3.393	7.55
	Clover (25% material)	.9102	.8108	6.201	6.89
	Clover (50% material)	.9070	.9433	2.159	8.23
	Clover (100% material)	.9268	.9726	1.761	7.36
	Clover (low density)	.9079	.8462	5.614	7.19
	Clover (high density)	.9180	.9723	1.173	7.75
GRASSES	Brome (all material)	.7845	.7845	6.4496	7.31
	Brome (25% material)	.8885	.6352	10.877	4.73
	Brome (50% material)	.9027	.7650	7.323	5.02
	Brome (100% material)	.8349	.7549	7.509	10.43
	Brome (low density)	.8612	.7394	7.404	6.02
	Brome (high density)	.8820	.6892	9.910	5.07
	Orchard (all material)	.7411	.7276	8.366	8.97
	Orchard (25% material)	.7496	.4844	12.935	5.92
	Orchard (50% material)	.8989	.8925	5.517	6.39
	Orchard (100% material)	.7466	.7962	9.010	10.54
	Orchard (low density)	.8075	.6598	10.643	6.90
	Orchard (high density)	.7195	.7963	7.487	10.67
MIXTURES	Brome/Alfalfa (all material)	.6474	.6474	10.971	11.85
	Brome/Alfalfa (25% material)	.6711	.6095	11.840	10.96
	Brome/Alfalfa (50% material)	.5400	.5682	12.450	13.10
	Brome/Alfalfa (100% material)	.7288	.7535	8.641	11.86
	Brome/Alfalfa (low density)	.6546	.6596	10.710	12.05
	Brome/Alfalfa (high density)	.6402	.6352	11.233	11.98
	Brome/Clover (all material)	.9434	.9434	1.827	5.51
	Brome/Clover (25% material)	.9201	.9233	2.632	6.97
	Brome/Clover (50% material)	.9804	.9047	3.200	2.99
	Brome/Clover (100% material)	.9439	1.0003	.331	6.00
	Brome/Clover (low density)	.9468	.9461	1.730	5.43
	Brome/Clover (high density)	.9400	.9407	1.924	5.75

[1] Root mean square error determined from SAS.
[2] Regression equations for all of particular crop test samples.
[3] Amount of mass in test fixture had two levels, low and high.

The other mixture, brome/alfalfa gave the largest moisture content prediction RMSE of 11.85 for all brome/alfalfa data. The RMSE for the 25%, 50%, and 100% tests were 10.96, 13.10, and 11.86 respectively. The correlation coefficients were 0.65 for all data, 0.67 for 25% material in the fixture, 0.54 for 50% material in the fixture, and 0.73 for 100% material in the fixture. Predicting the moisture content for grass, legumes, and mixture is not dependent on the amount of material in the test fixture.

Evaluation of Material Density on Moisture Content Prediction

The root mean square error and correlation coefficient for the crops and mixtures at the high and low densities are shown in figures 15 and 16. The graphs show that the two levels of density tested do not affect the moisture content predictive capability. There is no trend for the high or the low density to have higher predictive error, or greater correlation coefficients.

Graph of actual vs. predicted for the different materials tested are shown in figures 17-22, the different symbols represent the two densities. The two levels of density at each percentage material in the test fixture are shown in figures 17-22, with results showing that moisture prediction is density independent. The moisture content predictions for the different crops were not affected by the changes in density. The RMSE for moisture content prediction of alfalfa was 4.94 and 4.99 for the low and high-density levels while the correlation coefficient for low density is .9521 and .9574 for the high-density. The trend seen in alfalfa is similar for legumes as it is in grasses in mixtures. The RMSE for grasses and mixtures is not as accurate as for legumes, but the variance between the two density levels is less than 1.08 for all materials except for orchard. The slopes of the regression

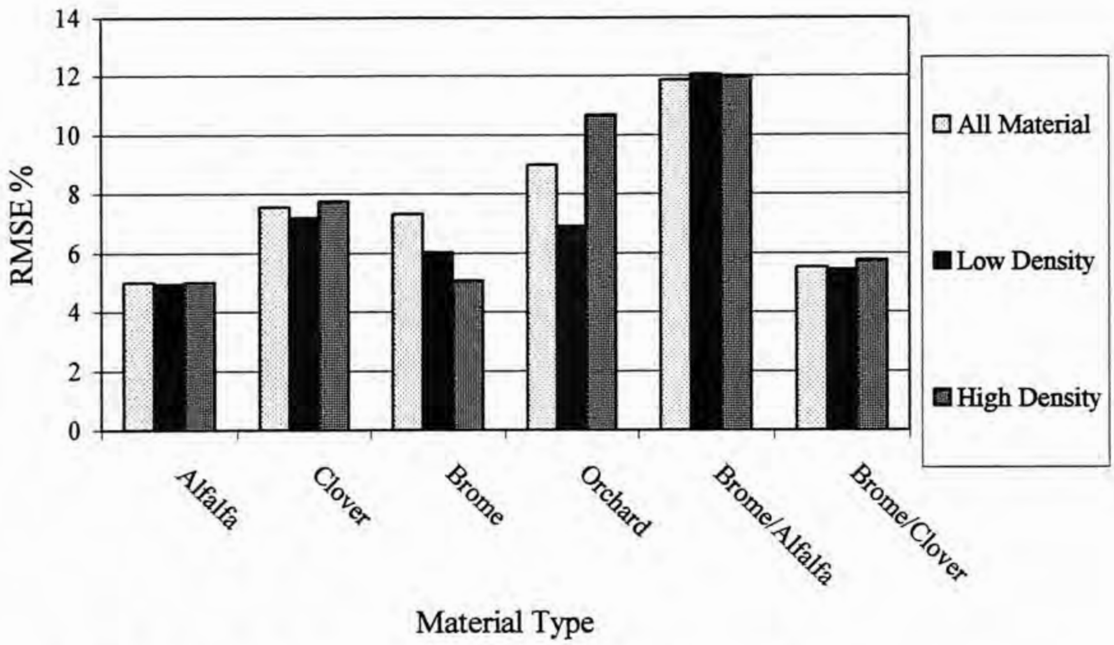

Figure 15. RMSE for all material at the two levels of density.

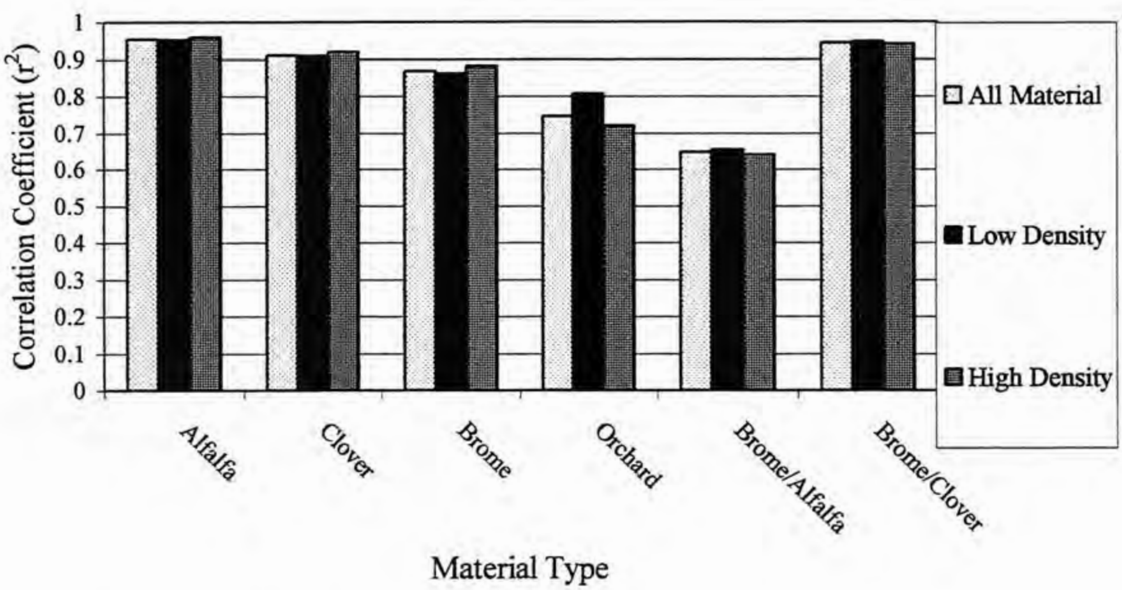

Figure 16. Correlation Coefficient for all material at the two levels of density

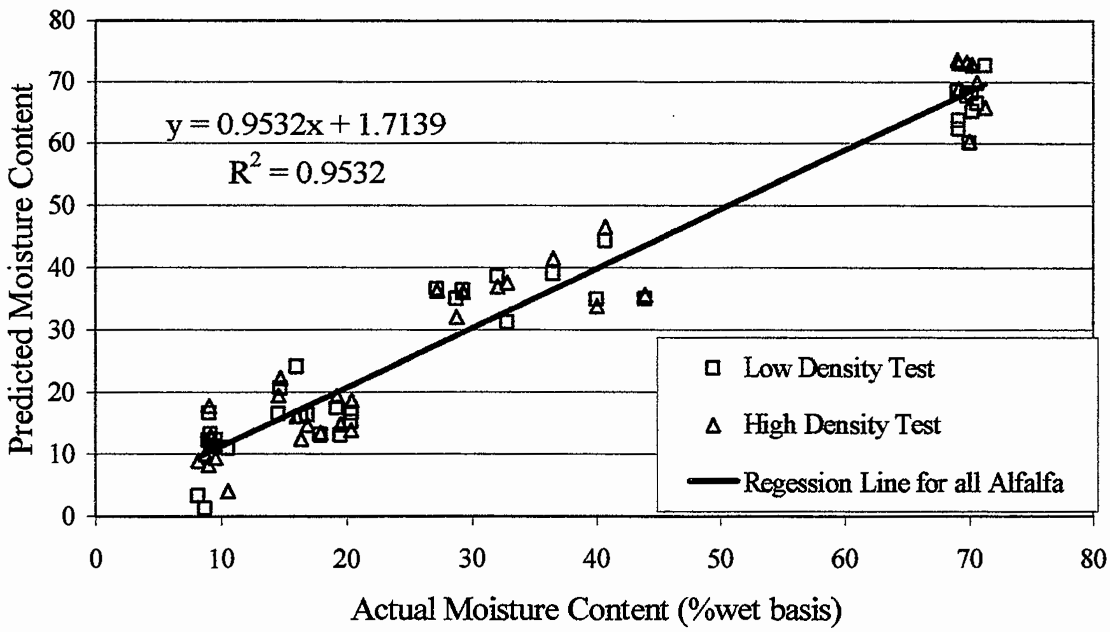

Figure 17. Regression line of actual moisture content vs. predicted moisture content for all alfalfa data. Different symbols are used to represent low and high densities for the different percentages of alfalfa in the fixture.

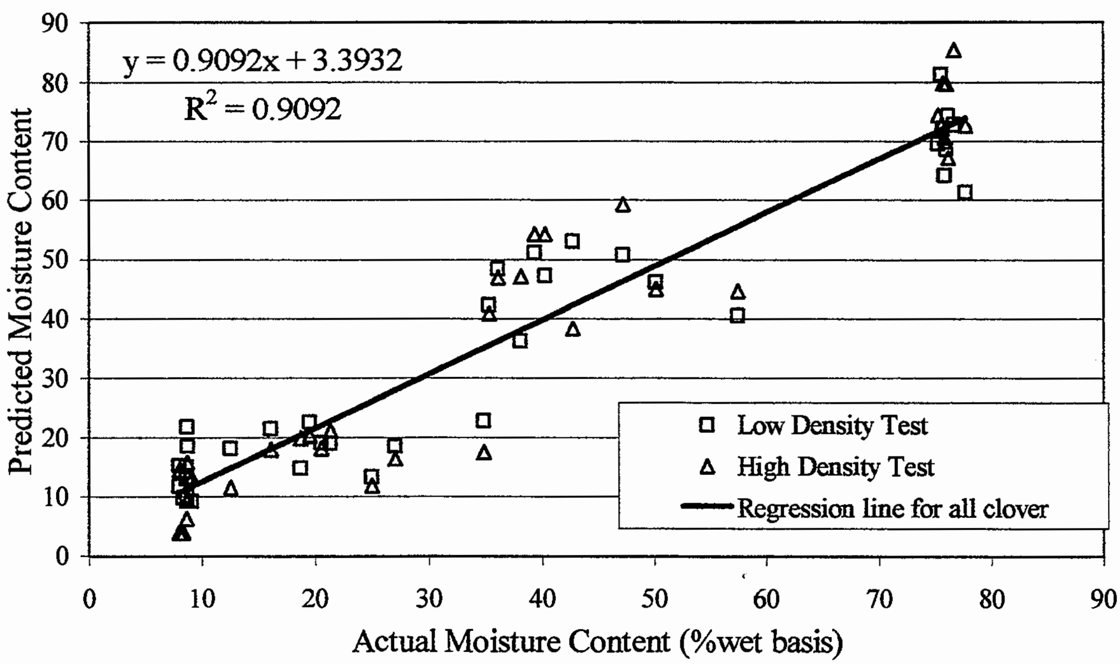

Figure 18. Regression line of actual moisture content vs. predicted moisture content for all clover data. Different symbols are used to represent low and high densities for the different percentages of clover in the fixture.

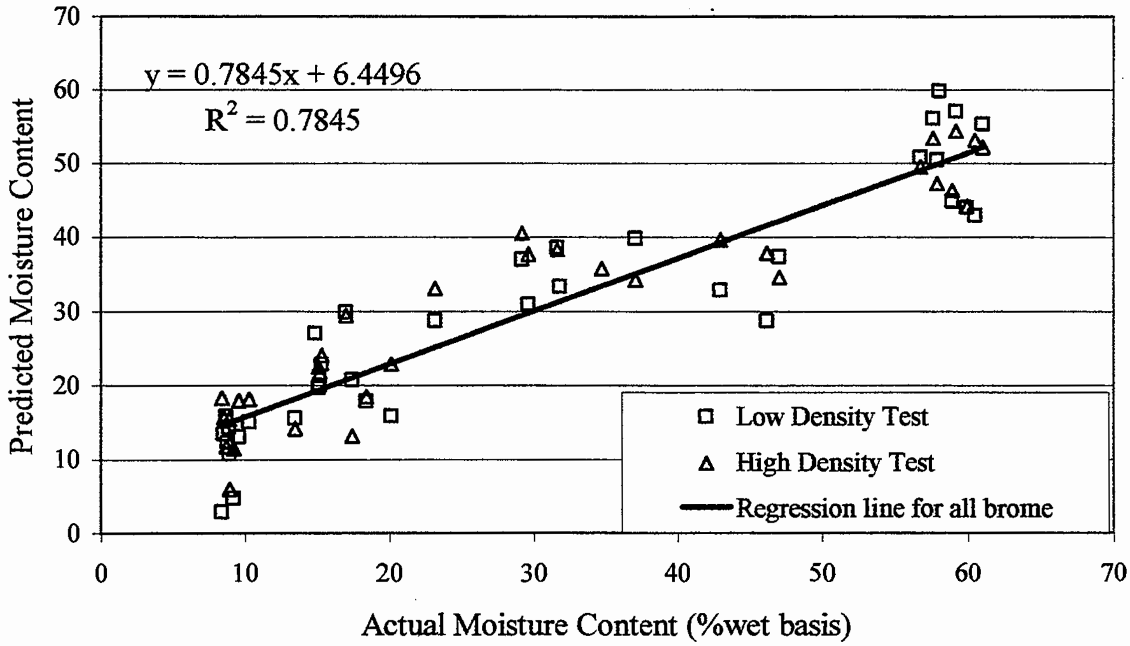

Figure 19. Regression line of actual moisture content vs. predicted moisture content for all brome data. Different symbols are used to represent low and high densities for the different percentages of brome in the fixture.

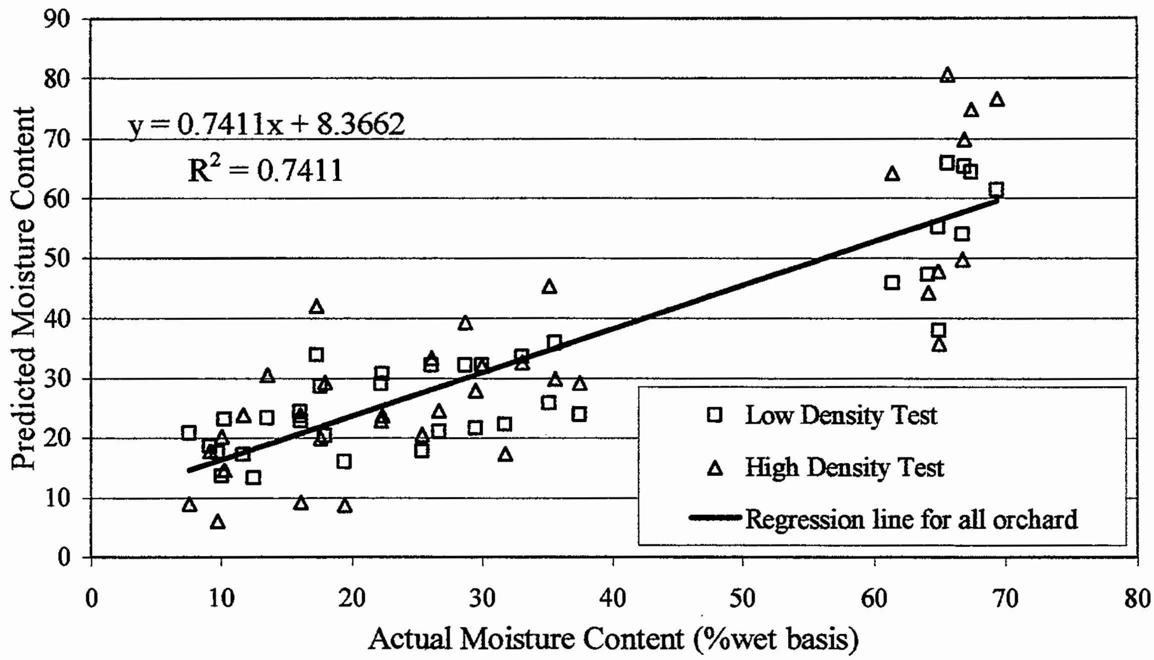

Figure 20. Regression line of actual moisture content vs. predicted moisture content for all orchard data. Different symbols are used to represent low and high densities for the different percentages of orchard in the fixture.

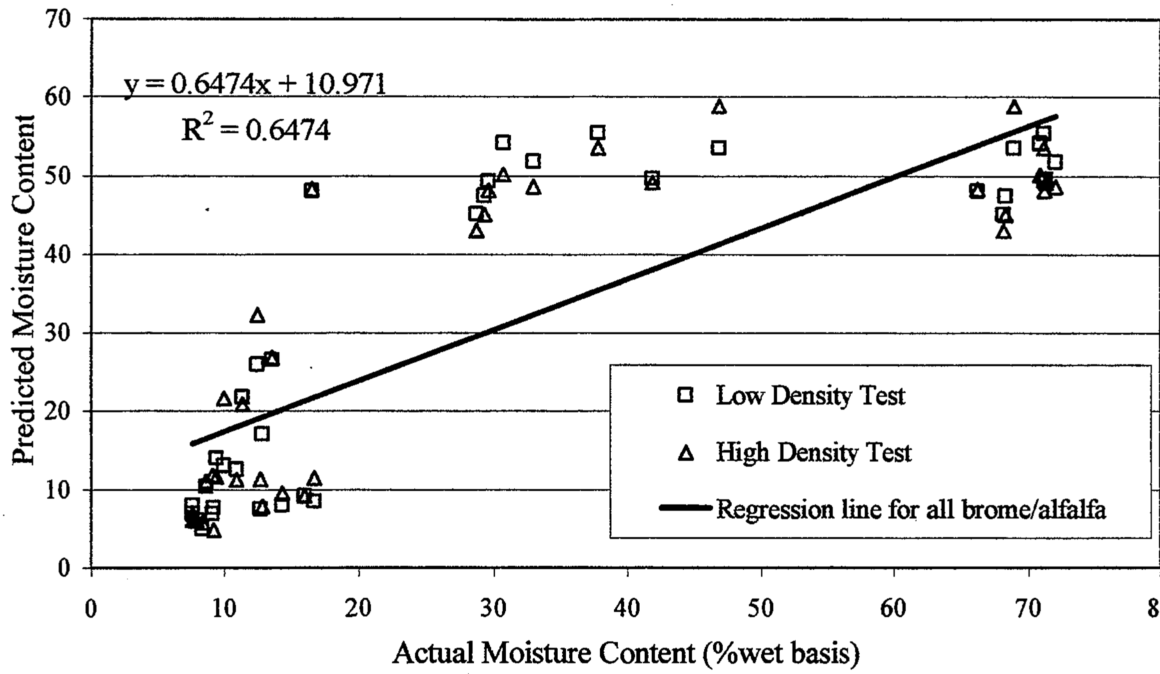

Figure 21. Regression line of actual moisture content vs. predicted moisture content for all brome/alfalfa data. Different symbols are used to represent low and high densities for the different percentages of brome/alfalfa in the fixture.

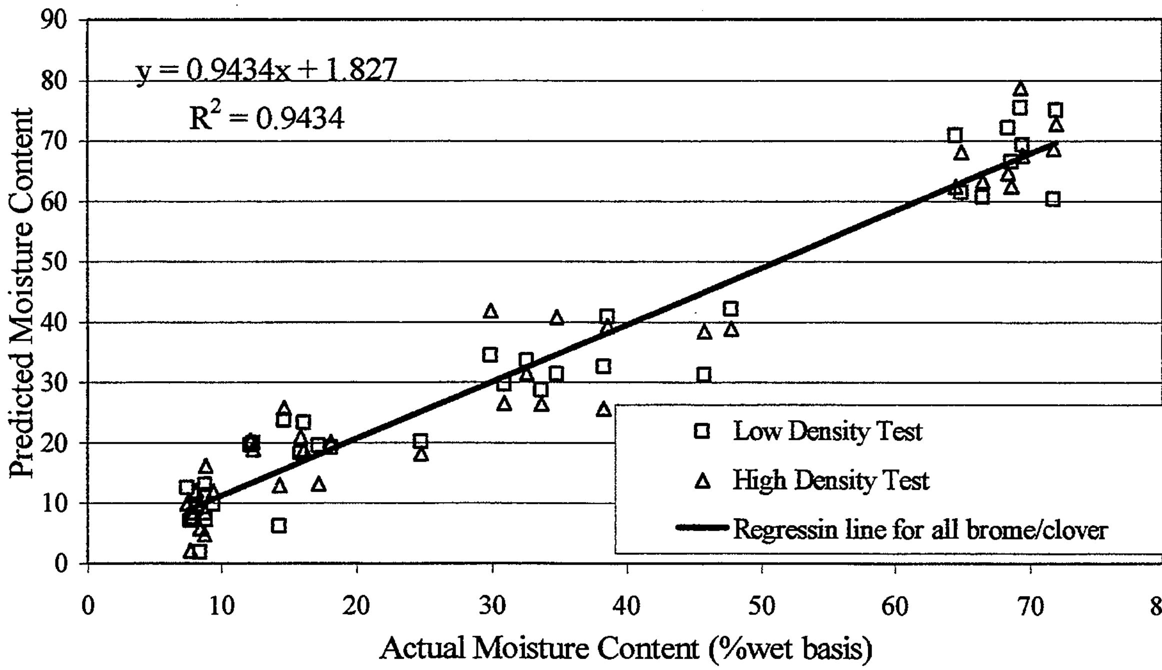

Figure 22. Regression line of actual moisture content vs. predicted moisture content for all brome/clover data. Different symbols are used to represent low and high densities for the different percentages of brome/clover in the fixture.

equations do not vary more than 0.14, which is the slope difference of the two densities of orchard. The variance in the correlation coefficients between the high and low densities of each material tested is less than 0.09.

Moisture content prediction for each material could be improved with better sampling techniques, and more even drying of the material. The variation in standardized moisture content in the 20% to 50% range decrease that ability to predict moisture content accuracy. The moisture content in the 20% to 50% range for brome/alfalfa shown in figures 13 and 21 indicates that sampling error affected the results of moisture content prediction. This was due to he uneven drying of mixtures and grasses, it could have been due to the sampling of the crops. Therefore the sub-sample tested may not have had the same moisture content as the sub-sample used in the standard procedure. Crop was placed on the floor and random sampled. In an attempt to have little variance in moisture content at the desired testing times the crop was flipped so drying would be even. That standardized moisture content results show crop did not dry evenly, and uneven drying could have caused some of the prediction error.

Evaluation of Material Type on Moisture Content Prediction

Figures 7, 8, 15, and 16 show that the material within the test fixture affects the moisture content predictive capability of the sensor. The moisture sensor that was developed is specific to each crop, and must be calibrated for each particular crop. Test results for the two legumes alfalfa and clover were much better than that of the grasses, brome and orchard, and the mixtures brome/alfalfa and brome/clover.

Results conclude that it is possible to determine moisture content of different forages independent ob bulk density, and percentage material in the fixture.

CONCLUSION

Results for predicting moisture content independent of density, and amount of material in fixture ranged from ± 3% to ± 13% for all six different materials tested. These ranges were determined from the RMSE (root mean square error) from the actual moisture content vs. the predicted moisture content of static samples of forage in the moisture range of 10 to 80 percent moisture wet basis.

Results have concluded that a forage moisture sensor capable of measuring moisture independent of density was developed in the frequency range of 900 KHz to 13 MHz with the exception of clover, which used 5 Hz as a prediction frequency. Prediction of moisture content is dependent on material, but is independent of density, and the percentage material in the test fixture. Future research in this area should lead to prediction equations that will predict material and a prediction equation can be used to solve for material, then the moisture content can be solved. The standardized moisture content in the high moisture range (above 65%) and the low moisture content (below 11%) had much less variation than the middle moisture contents (12-64%). The reason for narrow moisture content range is that the crop was tested immediately after it was cut. It had very little time to dry. At the low moisture content it had reached equilibrium moisture content. The middle moisture contents the crop dried unevenly, and the standardized moisture contents had a wide range. One way to improve results would to develop a better way to standardize drying and testing of standardized samples. Legume sample dried more evenly than grass and mixtures, and some of the prediction error may be caused by the standardized samples, not have the same moisture content as the sample tested in the fixture.

RECOMMENDATION FOR FUTURE STUDIES

A moisture sensor for real time moisture sensing of forages has potential to be demanded by farmers and ranchers. A parallel plate capacitor has many advantages for high production forage equipment, including moisture content prediction, as well as chemical analysis of the material.

Future studies should look at shielding the aluminum plates so no material touches the plates, this could remove noise in the sensor. Part of the error in prediction could be from the material touching the capacitor plates. The plates could be guarded with Rexolite. Only in the 100% material test did the material touch both plates, the 25% and 50% test the material only touched one capacitor plate.

Studies should also develop a standard method for equal drying of material, and random sampling in order to have standardized dried samples. Other areas of interest should be directed towards studies looking at how temperature and changes in humidity affect the dielectric properties, as well as what frequencies are best for identifying crop types so improved prediction equations can be found. In the near future a sensor will be developed that will predict moisture content, crop type, mass flow, and maybe even nutrients in the crop.

APPENDIX A

SOURCE CODE FOR CONTROL PROGRAM

```
DECLARE FUNCTION SciCon$ (dum)
DECLARE SUB conversion (intg, dec, dumvalue)
COMMON startf, stopf, stepf, sweepend, sampleid
DECLARE SUB Instructions ()
DECLARE FUNCTION InitMeter% (DevName$)
DECLARE SUB ReadIDString (device%)
DECLARE SUB TakeMeasurement (device%)
DECLARE SUB WriteCommand (device%, Cmd$)
DECLARE FUNCTION ReadValue% (device%, Buffer$, buflen%)
DECLARE SUB PrintErrors (ErrStr$)

CONST DEV = "Imp-ana"
CONST RESETCMD = "*RST"
CONST IDCMD = "*IDN?"
CONST MEASURECMD = "VAL?"

CONST BUFSIZE = 256        ' Size of IBRD buffer
CONST NULLCHAR = 2    ' Character to fill IBRD buffer with

CONST FALSE = 0
CONST TRUE = 1

'**************************************************'
' Name:     Global Variables Definition
'**************************************************
  DIM SHARED StatBits(20):
  DIM SHARED StatBits$(20)
  StatBits(0) = DCAS:  StatBits$(0) = "DCAS"
  StatBits(1) = DTAS:  StatBits$(1) = "DTAS"
  StatBits(2) = LACS:  StatBits$(2) = "LACS"
  StatBits(3) = TACS:  StatBits$(3) = "TACS"
  StatBits(4) = AATN:  StatBits$(4) = "AATN"
  StatBits(5) = CIC:   StatBits$(5) = "CIC"
  StatBits(6) = RREM:  StatBits$(6) = "RREM"
  StatBits(7) = LOK:   StatBits$(7) = "LOK"
  StatBits(8) = CMPL:  StatBits$(8) = "CMPL"
  StatBits(9) = eevent: StatBits$(9) = "EVENT"
  StatBits(10) = SPOLL: StatBits$(10) = "SPOLL"
  StatBits(11) = RQS:  StatBits$(11) = "RQS"
  StatBits(12) = SRQI: StatBits$(12) = "SRQI"
  StatBits(13) = EEND: StatBits$(13) = "EEND"
  StatBits(14) = TIMO: StatBits$(14) = "TIMO"
  StatBits(15) = EERR: StatBits$(15) = "EERR"
  StatBits(16) = 0:    StatBits$(16) = ""
```

```
' Error bits (in iberr%) and their names
  DIM SHARED ErrCodes(20):
  DIM SHARED ErrCodes$(20)
  ErrCodes(0) = EDVR:  ErrCodes$(0) = "EDVR"
  ErrCodes(1) = ECIC:  ErrCodes$(1) = "ECIC"
  ErrCodes(2) = ENOL:  ErrCodes$(2) = "ENOL"
  ErrCodes(3) = EADR:  ErrCodes$(3) = "EADR"
  ErrCodes(4) = EARG:  ErrCodes$(4) = "EARG"
  ErrCodes(5) = ESAC:  ErrCodes$(5) = "ESAC"
  ErrCodes(6) = EABO:  ErrCodes$(6) = "EABO"
  ErrCodes(7) = ENEB:  ErrCodes$(7) = "ENEB"
  ErrCodes(8) = EOIP:  ErrCodes$(8) = "EOIP"
  ErrCodes(9) = ECAP:  ErrCodes$(9) = "ECAP"
  ErrCodes(10) = EFSO: ErrCodes$(10) = "EFSO"
  ErrCodes(11) = EBUS: ErrCodes$(11) = "EBUS"
  ErrCodes(12) = ESTB: ErrCodes$(12) = "ESTB"
  ErrCodes(13) = ESRQ: ErrCodes$(13) = "ESRQ"
  ErrCodes(14) = ECFG: ErrCodes$(14) = "ETAB"
  ErrCodes(15) = ETAB: ErrCodes$(15) = "ECFG"

  ErrCodes(16) = 0:    ErrCodes$(16) = ""

  DIM SHARED Buffer$(BUFSIZE)
'*****************************************************
' Name:      Main Program
'
' This programs prints instructions on the screen, opens and
' initializes the Fluke voltmeter.  Reads and prints the meter's ID
' string.  Sets the' range of the meter and then goes into a
' measurement loop.  Each time around the loop it reads and prints
' a measurement from the meter and ' checks for a keypress.
' When a key is pressed the program terminates.
'*****************************************************
CLS
LOCATE 1, 1: COLOR 15
INPUT "Enter Filename  ", dumfilename$
FILENAME$ = "C:\JASON\DATA\" + dumfilename$
OPEN FILENAME$ FOR APPEND AS #2
INPUT "Enter number of Sweeps  ", sweepend
20  INPUT "Enter first sample #  ", sampleid
PRINT "First Sample_ID", sampleid
LOCATE 23, 1: COLOR 10
INPUT "Are you sure this is the correct sample # ? Y/N", C$
LOCATE 23, 1
PRINT "                                        "
        IF C$ = "n" THEN C$ = "N"
```

```
            IF C$ = "y" THEN C$ = "Y"
              IF C$ = "Y" THEN
              GOTO 15
            ELSE GOTO 20
15
END IF
LOCATE 9, 1: COLOR 15
numbfreq = 63
p = 1
PRINT #2, DATE$, TIME$
PRINT #2, "First_Sample_ID", sampleid
PRINT #2, "    Sample_ID      Sweep  ",
DO WHILE p < numbfreq + 1
PRINT #2, "Freq_" + LTRIM$(STR$(p)), "DSPLY_A" +
LTRIM$(STR$(p)), "DSPLY_B" + LTRIM$(STR$(p)),

p = p + 1
LOOP
PRINT #2, "END_OF_LINE"
10
  A$ = "Y"
WHILE A$ <> "q"
LOCATE 23, 1: COLOR 10
  INPUT "Do you wish to run another Sample Y/N", A$
  LOCATE 23, 1
  PRINT "                                              "
    IF A$ = "y" THEN A$ = "Y"
    IF A$ = "n" THEN A$ = "N"
    IF A$ = "N" THEN
      B$ = "N"
      A$ = "N"
      LOCATE 23, 1
      INPUT "Are you sure you wish to Quit Y/N? ", B$
      LOCATE 23, 1
      PRINT "                                              "
      IF B$ = "y" THEN B$ = "Y"
      IF B$ = "n" THEN B$ = "N"
      IF B$ = "Y" THEN
        A$ = "q"
        GOTO 100
      ELSE
        B$ = "N"
        A$ = "N"
        GOTO 10
          A$ = "N"
      END IF
```

```
        ELSE
          IF A$ = "Y" THEN
            LOCATE 23, 1
            INPUT "Are you sure you wish to run another
              sample Y/N   ", B$
            LOCATE 23, 1
            PRINT "                                          "
            IF B$ = "y" THEN
              B$ = "Y"
              A$ = "Y"
            END IF
            IF B$ = "n" THEN B$ = "N"
            IF B$ = "Y" THEN
              B$ = ""
              A$ = "N"
            END IF
          ELSE
          GOTO 10
          END IF
        END IF

IF A$ <> "Y" THEN
              LOCATE 8, 1: COLOR 10
              PRINT USING "\         \ ####  \          \"
 "SAMPLE_ID"; sampleid; "    Processing  "
'  Instructions
  FOR Sweep = 1 TO sweepend
    'SLEEP 2

    numbfreq = 5
    stepa = .001
    starta = .005
    stopa = .009
    DevName$ = DEV
    device% = InitMeter%(DevName$)
    CALL ReadIDString(device%)

    PRINT #2, sampleid, Sweep,
    Cmd$ = "A2B3F1V1C3"
    CALL WriteCommand(device%, Cmd$)
    LOCATE 15, 60: PRINT Cmd$

    Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
        LTRIM$(STR$(starta)) + "EN" +
        "PF" + LTRIM$(STR$(stopa)) + "EN"
    CALL WriteCommand(device%, Cmd$)
```

```
LOCATE 15, 30: PRINT Cmd$

Cmd$ = "W1 W2"
LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)

Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
  TakeMeasurement (device%)
NEXT C

'FOR jj = 1 TO 1000
'NEXT jj

'PRINT #2, "END_OF_SWEEP"

'SLEEP 2
numbfreq = 9
stepa = .01
starta = .01
stopa = .09
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
'PRINT #2, sampleid, Sweep,
  Cmd$ = "A2B3F1V1C3"
  LOCATE 15, 60: PRINT Cmd$
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
      LTRIM$(STR$(starta)) + "EN" + "PF" +
     LTRIM$(STR$(stopa)) + "EN"
CALL WriteCommand(device%, Cmd$)
  LOCATE 15, 30: PRINT Cmd$
  Cmd$ = "W1 W2"
  LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)
FOR C = 1 TO numbfreq
  TakeMeasurement (device%)
NEXT C
'PRINT #2, "END_OF_SWEEP"

'SLEEP 2
```

```
stepa = .1
starta = .1
stopa = .9
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
' PRINT #2, sampleid, Sweep,
  Cmd$ = "A2B3F1V1C3"
  LOCATE 15, 60: PRINT Cmd$
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
         LTRIM$(STR$(starta)) + "EN" + "PF" +
         LTRIM$(STR$(stopa)) + "EN"
CALL WriteCommand(device%, Cmd$)
  LOCATE 15, 30: PRINT Cmd$
  Cmd$ = "W1 W2"
  LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
  TakeMeasurement (device%)
NEXT C
'PRINT #2, "END_OF_SWEEP"

  'SLEEP 2
stepa = 1
starta = 1
stopa = 9
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
' PRINT #2, sampleid, Sweep,
  Cmd$ = "A2B3F1V1C3"
  LOCATE 15, 60: PRINT Cmd$
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
     LTRIM$(STR$(starta)) + "EN" + "PF" +
     LTRIM$(STR$(stopa)) + "EN"
CALL WriteCommand(device%, Cmd$)
  LOCATE 15, 30: PRINT Cmd$
  Cmd$ = "W1 W2"
  LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "EX"
```

```
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
  TakeMeasurement (device%)
NEXT C

'SLEEP 2
stepa = 10
starta = 10
stopa = 90
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
' PRINT #2, sampleid, Sweep,
  Cmd$ = "A2B3F1V1C3"
  LOCATE 15, 60: PRINT Cmd$
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
     LTRIM$(STR$(starta)) + "EN" + "PF" +
     LTRIM$(STR$(stopa)) + "EN"
CALL WriteCommand(device%, Cmd$)
  LOCATE 15, 30: PRINT Cmd$
  Cmd$ = "W1 W2"
  LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)
  Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
  TakeMeasurement (device%)
NEXT C
'PRINT #2, "END_OF_SWEEP"

'SLEEP 2
stepa = 100
starta = 100
stopa = 900
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
' PRINT #2, sampleid, Sweep,
  Cmd$ = "A2B3F1V1C3"
  LOCATE 15, 60: PRINT Cmd$
  CALL WriteCommand(device%, Cmd$)
  Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
     LTRIM$(STR$(starta)) + "EN" + "PF" +
```

```
        LTRIM$(STR$(stopa)) + "EN"
    CALL WriteCommand(device%, Cmd$)
    LOCATE 15, 30: PRINT Cmd$
    Cmd$ = "W1 W2"
    LOCATE 16, 1: PRINT "Sweep Number"; Sweep
    CALL WriteCommand(device%, Cmd$)
    Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
    TakeMeasurement (device%)
NEXT C

'SLEEP 2
stepa = 1000
starta = 1000
stopa = 9000
DevName$ = DEV
device% = InitMeter%(DevName$)
CALL ReadIDString(device%)
' PRINT #2, sampleid, Sweep,
    Cmd$ = "A2B3F1V1C3"
    LOCATE 15, 60: PRINT Cmd$
CALL WriteCommand(device%, Cmd$)
    Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
        LTRIM$(STR$(starta)) + "EN" + "PF" +
        LTRIM$(STR$(stopa)) + "EN"
CALL WriteCommand(device%, Cmd$)
    LOCATE 15, 30: PRINT Cmd$
    Cmd$ = "W1 W2"
    LOCATE 16, 1: PRINT "Sweep Number"; Sweep
CALL WriteCommand(device%, Cmd$)
    Cmd$ = "EX"
CALL WriteCommand(device%, Cmd$)

FOR C = 1 TO numbfreq
     TakeMeasurement (device%)
NEXT C
'PRINT #2, "END_OF_SWEEP"

    'SLEEP 2
numbfreq = 4
stepa = 1000
starta = 10000
stopa = 13000
DevName$ = DEV
```

```
      device% = InitMeter%(DevName$)
      CALL ReadIDString(device%)
     ' PRINT #2, sampleid, Sweep,
        Cmd$ = "A2B3F1V1C3"
        LOCATE 15, 60: PRINT Cmd$
      CALL WriteCommand(device%, Cmd$)
                Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
        LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
      CALL WriteCommand(device%, Cmd$)
        LOCATE 15, 30: PRINT Cmd$
        Cmd$ = "W1 W2"
        LOCATE 16, 1: PRINT "Sweep Number"; Sweep
      CALL WriteCommand(device%, Cmd$)
        Cmd$ = "EX"
      CALL WriteCommand(device%, Cmd$)

      FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
      NEXT C
      PRINT #2, "END_OF_SWEEP"

   NEXT Sweep
BEEP
SLEEP 2
BEEP
SLEEP 2
BEEP
       sampleid = sampleid + 1
END IF
p = 1

WEND
100
CLOSE #2

'***************************************************
' Name:       InitMeter
' Arguments:  DevName - name of GPIB device
' Returns:    device handle of voltmeter
'
' Description: Opens the device, sets the system timeout to 3
'  seconds,  sends a reset command to the voltmeter.
'  Returns the GPIB  device handle.
'*****************************************************
'FUNCTION InitMeter% (DevName$) STATIC
   CALL IBFIND(DevName$, device%)      ' Open the device
```

```
  IF device% < 0 AND IBERR% = EDVR THEN
     PRINT "IBFIND Couldn't find device "; DevName$
     PRINT "   Make sure that you have assigned the name"
            DevName$; "to the"
     PRINT "   meter with the CBCONF.EXE program.
             Make sure that the meter is"
     PRINT "   configured for the address that you specified with
            CBCONF.EXE."
     END
  ELSEIF device% < 0 AND IBERR% = ECFG THEN
     PRINT "Board is not configured correctly"
     PRINT "   The board type that is set in GPIB.CFG file
            does not match the"
     PRINT "   board that is installed.  Run the CBCONF.EXE
           program and check"
     PRINT "   the board type that is set there and make sure it
           matches the"
     PRINT "   board that you have installed in your system."
  END IF
 IBSTA& = ILTMO%(device%, T5s)              ' Set the timeout
  CALL WriteCommand(device%, RESETCMD)
 ' Send reset command
range
  InitMeter% = device%                ' Return the device handle
END FUNCTION
'***********************************************************'
' Name:      Instructions
' Arguments:  ---
'
' Description: Prints the programs instructions
'***********************************************************
SUB Instructions STATIC
  CLS
  LOCATE 1, 20
  PRINT "QuickBASIC Example GPIB Program"
  LOCATE 3, 1
  PRINT "This is a program requires user input to communicate
        with an"
  PRINT "   4192A LF IMPEDANCE ANALYER 5Hz-13MHz"
  PRINT ""
  PRINT "The program expects that the 4192A LFIMPEDANCE
        ANALYER has already been"
  PRINT "installed with the CBCONF.EXE program and been
        given the name HO3 ."
  PRINT ""
  PRINT "             --- Press any key to start ---"
```

```
  DO WHILE INKEY$ = ""
    LOOP

END SUB
'**************************************************'
' Name:        PrintErrors
' Arguments:   ---
' Description: Prints the global GPIB status and error codes
'**************************************************
SUB PrintErrors (ErrStr$) STATIC

  PRINT CHR$(7);        ' Beep the speaker

  LOCATE 20, 1
  PRINT "   *** ERROR ***"; ErrStr$
  PRINT "   Error codes:  ibsta% = 0x"; HEX$(IBSTA%); " (";
  i = 0
  DO WHILE StatBits$(i) <> ""       ' Print names for status bits
    IF IBSTA% AND StatBits(i) THEN
      PRINT StatBits$(i); " ";
    END IF
    i = i + 1
  LOOP
  PRINT ")"

  LOCATE 22, 1
  PRINT SPACE$(70)
  LOCATE 22, 1
  PRINT "               iberr% ="; IBERR%; " (";
  i = 1
  DO WHILE ErrCodes$(i) <> ""
    IF IBERR% = ErrCodes(i) THEN
      PRINT ErrCodes$(i); ")"
    END IF
    i = i + 1
  LOOP

  LOCATE 23, 1
  PRINT "               ibcnt% ="; IBCNT%; "       "
END SUB

'**************************************************
' Name:        ReadIDString
' Arguments:   device% - GPIB device handle returned by ibfind
' Description: Sends commnd to volt meter that tells it to return its
'              identification string.  Prints the string on the screen
```

```
'********************************************
SUB ReadIDString (device%) STATIC

 CALL WriteCommand(device%, IDCMD)       ' Send command
  IF ReadValue(device%, Buffer$, BUFSIZE) = TRUE THEN
  ' Read response
    LOCATE 14, 1
    PRINT "IMPEDANCE ANALYZER ID = "; 4192
 ' Print response
  END IF
END SUB
'********************************************

FUNCTION ReadValue% (device%, rdbuf$, BUFSIZE%)
        STATIC
  rdbuf$ = STRING$(BUFSIZE - 1, NULLCHAR)  ' Clear string
  IBSTA% = ILRD%(device%, rdbuf$)          ' Read from GPIB
  IF (IBSTA% AND EERR) THEN               ' Check for erros
    PrintErrors ("IBRD failed")
    ReadValue% = FALSE
  ELSE
    ReadValue% = TRUE
    i = 1
    DO WHILE MID$(rdbuf$, i, 1) <> CHR$(NULLCHAR)
      i = i + 1
      LOOP
    rdbuf$ = LEFT$(rdbuf$, i - 2)
  END IF
END FUNCTION

FUNCTION SciCon$ (dum)
freqdum = dum
fdum = LOG(freqdum) / LOG(10)
fint = INT(fdum)
fdec = fdum - fint
'fdec = 10 ^ fdec * 10000
'fint = fint - 4
fdec = (10 ^ fdec)
fint = fint

SciCon$ = STR$(fdec) + "E" + LTRIM$(STR$(fint))

END FUNCTION

'********************************************
' Name:     TakeMeasurement
```

```
' Arguments:   device% - GPIB device handle returned by ibfind
' Description: Sends a command to the voltmeter that tells it to
'          take a measurement and return it over the GPIB.
'          Reads the measurement value and prints it on the screen.
'**********************************************************
SUB TakeMeasurement (device%) STATIC

IF ReadValue%(device%, Buffer$, BUFSIZE) = TRUE THEN
 ' Read response
      LOCATE 17, 1
      'PRINT "DISPLAY A AND B = "; BUFFER$;
 ' Print response
       PRINT "DISPLAY A = "; MID$(Buffer$, 5, 11)
 ' Print response
       PRINT "DISPLAY B = "; MID$(Buffer$, 22, 11)
 ' Print response
       PRINT "FREQUENCY ="; MID$(Buffer$, 36, 10)
      'PRINT #2, "DISPLAY A AND B = "; BUFFER$;
 ' Print response
       PRINT #2, MID$(Buffer$, 36, 10),
       PRINT #2, MID$(Buffer$, 5, 11),
       PRINT #2, MID$(Buffer$, 22, 11),

  END IF

END SUB
'**********************************************************
' Name:        WriteCommand
' Arguments:   device% - GPIB device handle returned by ibfind
'          cmd$ - String containing command
' Description: Writes the command to the GPIB device and then
'          checks for errors.
'**********************************************************
SUB WriteCommand (device%, Cmd$) STATIC

CALL IBWRT(device%, Cmd$)
  IF (IBSTA% AND EERR) THEN
    ErrStr$ = "IBWRT failed while writing " + Cmd$
    PrintErrors (ErrStr$)
  END IF
END SUB
```

APPENDIX B

RAW DATA

Table A-1. Raw data for alfalfa moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		74.3	39.7	
2		open				50		74.5	39.3	
3		open				100		74.6	39.1	
4	958	alfalfa	73.57	145.87	94.85	25	202.6	74.9	38.7	70.57
5	958	alfalfa				25	404	75	38.9	
6	953	alfalfa	75.51	135.35	93.59	50	400.7	75.1	38.2	69.79
7	953	alfalfa				50	799.9	75.3	37.5	
8	939	alfalfa	75.02	155.58	99.98	100	801.4	75.5	37.8	69.02
9	939	alfalfa				100	1601.2	75.7	37.5	
10		open				25		75.7	37.8	
11		open				50		75.7	37.4	
12		open				100		75.8	37.4	
13	954	alfalfa	76.98	147.26	98.71	25	201.2	75.8	37.1	69.08
14	954	alfalfa				25	402.4	76.1	36.4	
15	933	alfalfa	76.9	160.86	101.93	50	402.3	76.2	36.4	70.19
16	933	alfalfa				50	803.9	76	36.3	
17	945	alfalfa	75.71	157.34	99.15	100	799.9	76	35.9	71.29
18	945	alfalfa				100	1599.5	76.2	35.7	
19		open				25		75.4	35.9	
20		open				50		75.8	35.9	
21		open				100		75.5	35.6	
22	944	alfalfa	74.67	140.43	94.42	25	199.9	75.5	35.5	69.97
23	944	alfalfa				25	399.8	75.3	35.2	
24	942	alfalfa	75.42	152.34	99.2	50	397.8	75.8	35.1	69.08
25	942	alfalfa				50	797.3	76	34.8	
26	936	alfalfa	74.62	143.05	94.98	100	801.6	75.9	34.9	70.25
27	936	alfalfa				100	1600.8	75.5	34.3	

Table A-2. Raw data for alfalfa moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		71.9	37.8	
2		open				50		72	37.6	
3		open				100		72.1	37.3	
4	1206	alfalfa	76.05	104.96	94.4	25	60.4	72	37.1	36.53
5	1206	Alfalfa				25	121.3	71.9	37	
6	1228	alfalfa	74.46	105.84	93.08	50	120.6	71.9	37	40.66
7	1228	alfalfa				50	241.2	72	36.7	
8	1203	alfalfa	76.18	101.78	93.58	100	240.6	72	36.6	32.03
9	1203	alfalfa				100	480.9	71.8	36.4	
10		open				25		71.7	36.2	
11		open				50		71.7	36.4	
12		open				100		71.6	36.5	
13	917	alfalfa	76	105.02	96.53	25	60.7	71.6	36.7	29.26
14	917	alfalfa				25	120.9	71.4	36	
15	1202	alfalfa	76.21	105.91	97.38	50	119.8	71.3	36.2	28.72
16	1202	alfalfa				50	239.9	71	36	
17	1230	alfalfa	75	103.13	91.88	100	240.8	70.9	35.7	39.99
18	1230	alfalfa				100	481.3	70.8	35.5	
19		open				25		70.9	35.7	
20		open				50		70.8	35.7	
21		open				100		70.7	35.6	
22	1227	alfalfa	75.2	102.31	90.42	25	60.7	70.7	35.1	43.86
23	1227	alfalfa				25	120.3	70.5	35.4	
24	1220	alfalfa	75.87	105.27	95.63	50	120.8	70.4	35.2	32.79
25	1220	alfalfa				50	241.5	70.3	35.3	
26	1205	alfalfa	74.33	104.35	96.19	100	240.5	70.3	35.1	27.18
27	1205	alfalfa				100	480.8	70.2	34.9	

Table A-3. Raw data for alfalfa moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		67.3	35.1	
2		open				50		67.7	34.7	
3		open				100		67.8	34.3	
4	906	alfalfa	76.07	94.63	91.07	25	49.9	68	34.5	19.18
5	906	alfalfa				25	100.3	68.3	34.5	
6	908	alfalfa	75.92	94.74	91.07	50	98.7	68.3	34.1	19.50
7	908	alfalfa				50	199.7	68.5	34.9	
8	910	alfalfa	77.17	100.83	96.6	100	200.1	68.6	35.3	17.88
9	910	alfalfa				100	400.3	68.6	35.2	
10		open				25		68.5	35.6	
11		open				50		68.4	35.6	
12		open				100		68.3	35.2	
13	916	alfalfa	75.02	97.64	93.03	25	49.6	68.3	35.2	20.38
14	916	alfalfa				25	99.9	68.3	34.8	
15	921	alfalfa	75.4	92.95	89.39	50	100.6	68.4	35	20.28
16	921	alfalfa				50	200.9	68.5	35.6	
17	904	alfalfa	77.22	103.29	99.46	100	198.6	68.3	36	14.69
18	904	alfalfa				100	399.8	68.4	35.8	
19		open				25		68.3	35.4	
20		open				50		68.2	35.3	
21		open				100		68.5	35.7	
22	923	alfalfa	76.6	101.91	97.64	25	50	68.5	35.9	16.87
23	923	alfalfa				25	100.9	68.5	35.9	
24	905	alfalfa	74.87	97.9	94.13	50	100.2	68.3	35.7	16.37
25	905	alfalfa				50	200.2	68	35.4	
26	907	alfalfa	76.39	92.7	90.33	100	200.6	68	35	14.53
27	907	alfalfa				100	401.2	68	35	

Table A-4. Raw data for alfalfa moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		68.6	32.3	
2		open				50		68.7	32.5	
3		open				100		68.6	32.6	
4	1658	alfalfa	74.26	93.75	91.97	25	41	68.1	32.3	9.13
5	1658	alfalfa				25	83.4	67.7	32.7	
6	1654	alfalfa	74.96	110.59	107.37	50	79.2	67.5	32.4	9.04
7	1654	alfalfa				50	173	67.3	32.5	
8	1657	alfalfa	74.69	94.79	92.98	100	169.5	67.6	32.4	9.00
9	1657	alfalfa				100	350.4	68.1	32.3	
10		open				25		68.3	32.6	
11		open				50		68.7	32.2	
12		open				100		69	32.1	
13	1637	alfalfa	75.03	95.65	92.35	25	41.1	69.1	31.9	16.00
14	1637	alfalfa				25	83.1	69.3	31.9	
15	1641	alfalfa	76.04	95.37	93.56	50	81	69.4	31.6	9.36
16	1641	alfalfa				50	171	69.5	31.6	
17	1660	alfalfa	75.48	89.39	88.06	100	168	69.8	31.4	9.56
18	1660	alfalfa				100	350.8	70.1	31.8	
19		open				25		70.1	31.8	
20		open				50		70.3	31.7	
21		open				100		70.3	31.4	
22	1665	alfalfa	74.64	99.79	97.59	25	42.1	70.3	31.1	8.75
23	1665	alfalfa				25	85	70.1	31.4	
24	1659	alfalfa	76.5	100.87	98.88	50	82.6	70.2	31.1	8.17
25	1659	alfalfa				50	173.8	70.3	31.1	
26	1655	alfalfa	76.49	99.5	97.07	100	172.1	70.5	30.8	10.56
27	1655	alfalfa				100	355	70.5	30.7	

Table A-5. Raw data for clover moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		72.6	38.1	
2		open				50		72.9	38.1	
3		open				100		72.9	38.6	
4	951	clover	78.66	161.88	97.24	25	200.9	73.1	38.9	77.67
5	951	clover				25	401.6	73.2	39.5	
6	949	clover	74.79	148.55	92.53	50	400.2	73.2	39.6	75.95
7	949	clover				50	801.1	73.3	40.1	
8	947	clover	76.1	152.54	94.86	100	799.6	72.1	40.2	75.46
9	947	clover				100	1600.1	73.2	40.2	
10		open				25		73.4	40.6	
11		open				50		73.3	40.6	
12		open				100		73.3	40.9	
13	948	clover	74.23	149.22	92.39	25	200.2	73.3	40.9	75.78
14	948	clover				25	400.1	73.4	40.9	
15	943	clover	76.03	146.53	93.2	50	400.5	73.6	40.8	75.65
16	943	clover				50	800.8	73.6	40.7	
17	955	clover	76.43	151.47	93.97	100	800.1	73.6	40.4	76.63
18	955	clover				100	1599.5	73.7	40.4	
19		open				25		73.8	40.4	
20		open				50		73.9	40.2	
21		open				100		74	40.4	
22	946	clover	77.18	205.64	108.23	25	199.6	74.1	40.1	75.83
23	946	clover				25	399.7	73.8	40.2	
24	959	clover	76.93	156.03	96.55	50	400.9	73.9	39.6	75.20
25	959	clover				50	802.1	73.8	39.2	
26	937	clover	74.91	163.37	96.04	100	799	73.9	38.9	76.11
27	937	clover				100	1601.9	73.8	38.8	

Table A-6. Raw data for clover moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		70.6	38.7	
2		open				50		70.8	38.8	
3		open				100		70.9	38.9	
4	1229	clover	74.76	105.41	94.6	25	61.6	71.4	38.7	35.27
5	1229	clover				25	120.6	71.2	39	
6	1216	clover	75.22	101.54	90.94	50	120.4	71.3	38.9	40.27
7	1216	clover				50	240.7	71.3	39	
8	1217	clover	75.28	124.38	103.38	100	239.9	71.4	39.5	42.77
9	1217	clover				100	479.5	71.4	39.3	
10		open				25		71.2	39.7	
11		open				50		71.4	40.1	
12		open				100		71.6	40.3	
13	1201	clover	74.37	108.68	96.29	25	59.1	71.4	40.3	36.11
14	1201	clover				25	119.1	71.2	40.8	
15	1204	clover	76.42	107.09	95.03	50	119.7	71.6	40.8	39.32
16	1204	clover				50	240.1	71.3	40.9	
17	1221	clover	76.73	102.94	92.96	100	239.5	71.6	40.9	38.08
18	1221	clover				100	479.5	71.7	40.8	
19		open				25		71.8	40.5	
20		open				50		71.6	40.3	
21		open				100		71.8	40.1	
22	1223	clover	75.99	123.21	99.55	25	60.7	71.8	39.9	50.11
23	1223	clover				25	121.2	71.9	39.8	
24	1224	clover	74.69	129.27	97.91	50	120.1	71.9	39.7	57.46
25	1224	clover				50	240.1	71.8	39.6	
26	1222	clover	76.37	113.11	95.78	100	239.9	71.8	39.5	47.17
27	1222	clover				100	480.5	72	39.2	

Table A-7. Raw data for clover moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		67.4	33.8	
2		open				50		67.6	33.7	
3		open				100		67.9	33.4	
4	912	clover	75.33	94.5	90.77	25	49.8	67.4	33.1	19.46
5	912	clover				25	99.7	67.3	32.9	
6	920	clover	75.25	92.29	88.8	50	100	67.1	32.8	20.48
7	920	clover				50	200.2	67.1	32.8	
8	1213	clover	75.72	91.3	89.35	100	200.5	67	32.7	12.52
9	1213	clover				100	400.4	67.8	33	
10		open				25		68	33.4	
11		open				50		67.8	33.2	
12		open				100		67.9	33.4	
13	911	clover	74.23	95.23	89.99	25	50.9	68.1	33.5	24.95
14	911	clover				25	101	68.2	33.3	
15	913	clover	76.71	91.54	89.16	50	99.8	68.3	33.3	16.05
16	913	clover				50	200	68.3	33.7	
17	903	clover	73.82	94.37	89.99	100	200	68.5	33.3	21.31
18	903	clover				100	400.6	68.5	33.8	
19		open				25		68.5	33.7	
20		open				50		68.4	34.6	
21		open				100		68.5	34.6	
22	924	clover	76.46	93.31	90.16	25	50.1	68.6	35.1	18.69
23	924	clover				25	100.4	68.6	35	
24	909	clover	75.39	99.36	92.89	50	100.5	68.7	34.8	26.99
25	909	clover				50	200.1	68.8	35.4	
26	915	clover	75.07	110.77	98.34	100	200.3	68.8	35.6	34.82
27	915	clover			98.34	100	400.5	68.5	35.4	

Table A-8. Raw data for clover moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		66.3	30.6	
2		open				50		66.5	30.8	
3		open				100		66.4	31.2	
4	1679	clover	74.68	87.16	86.02	25	40.6	66.4	30.7	9.13
5	1679	clover				25	91.4	66.7	31.1	
6	1656	clover	76.52	88.85	87.78	50	80.8	66.9	31.2	8.68
7	1656	clover				50	171.3	66.8	31.1	
8	1680	clover	76.64	90.64	89.41	100	171.4	66.8	30.9	8.79
9	1680	clover				100	350.8	66.9	30.8	
10		open				25		67	31.2	
11		open				50		66.9	31	
12		open				100		67.1	31	
13	1622	clover	75.85	87.01	86.04	25	41.4	67.2	31.1	8.69
14	1622	clover				25	81.5	67.3	31.5	
15	1669	clover	74.45	86.49	85.48	50	81.2	67.4	31.3	8.39
16	1669	clover				50	172.7	67.5	31.6	
17	1623	clover	75.1	93.48	91.88	100	170.5	67.6	31.7	8.71
18	1623	clover				100	352.9	67.1	31.6	
19		open				25		66.8	31.5	
20		open				50		66.7	31.9	
21		open				100		67.2	31.9	
22	1670	clover	74.58	94.15	92.58	25	40.8	67.4	31.5	8.02
23	1670	clover				25	81.1	67.8	31.7	
24	1668	clover	72.25	90.55	89.08	50	80.8	67.9	32.1	8.03
25	1668	clover				50	172	68.1	31.8	
26	1636	clover	76.04	88.75	87.65	100	172.5	68.3	32.1	8.65
27	1636	clover				100	353.7	68.4	32	

Table A-9. Raw data for brome moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		69.9	35.2	
2		open				50		70	35.3	
3		open				100		70.2	35	
4	1035	brome	74.4	123.9	94.62	25	200.6	70.2	35.5	59.15
5	1035	brome				25	404.6	69.5	35.9	
6	1037	brome	73.37	116.59	90.23	50	401.4	69.1	35.7	60.99
7	1037	brome				50	804.2	68.6	35.8	
8	1626	brome	74.12	118.24	91.55	100	801.5	68.6	36.2	60.49
9	1626	brome				100	1603.7	69.2	35.2	
10		open				25		69.3	35	
11		open				50		69.3	34.8	
12		open				100		69.2	34.7	
13	1627	brome	74.91	135.21	99.09	25	199.9	69.4	34.4	59.90
14	1627	brome				25	401	69.4	34.2	
15	1629	brome	74.37	137.2	100.87	50	402.1	69.2	34	57.82
16	1629	brome				50	803.1	69.8	33.8	
17	1630	brome	75.03	160.5	110.91	100	804	70.1	33.8	58.02
18	1630	brome				100	1602.9	70.2	33.7	
19		open				25		70.5	34.2	
20		open				50		70.6	34.1	
21		open				100		70.5	34.2	
22	1639	brome	74.06	150.24	105.38	25	201.3	70.4	33.8	58.89
23	1639	brome				25	402.8	70.5	33.9	
24	1638	brome	74.99	111.3	90.73	50	400.9	71	33.8	56.65
25	1638	brome				50	803.8	71.3	33.9	
26	1628	brome	75.54	136.11	101.25	100	801	71.7	33.8	57.55
27	1628	brome				100	1605.3	71.8	32.9	

Table A-10. Raw data for brome moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		66.1	30.5	
2		open				50		66.3	30.5	
3		open				100		66.1	30	
4	1667	brome	75.69	110.91	99.72	25	60.4	66.3	30	31.77
5	1667	brome				25	121.5	66.3	30.1	
6	1666	brome	74.71	115.9	102.88	50	120.5	66.4	30.2	31.61
7	1666	brome				50	242.4	66.7	30.9	
8	1678	brome	74.57	117.62	104.87	100	241	66.7	30.7	29.62
9	1678	brome				100	491.2	66.8	30.6	
10		open				25		67.2	30.4	
11		open				50		67.4	30.9	
12		open				100		67.3	31	
13	1178	brome	73.71	110.81	93.37	25	60.1	67.3	31.2	47.01
14	1178	brome				25	122	67.3	31	
15	1663	brome	76.78	117.62	105.71	50	170.2	67.5	30.9	29.16
16	1663	brome				50	240.2	67.6	30.9	
17	1651	brome	74.39	97.5	92.15	100	239.4	67.8	30.9	23.15
18	1651	brome				100	490.2	67.8	31	
19		open				25		67.9	30.9	
20		open				50		68	31.5	
21		open				100		68.1	31.6	
22	1672	brome	75.14	111.47	98	25	60.3	68.3	31.4	37.08
23	1672	brome				25	120.8	67.8	31.1	
24	1671	brome	74.57	119.78	100.37	50	121.3	67.8	31.6	42.93
25	1671	brome				50	240	67.9	31.7	
26	1673	brome	72.84	136	106.83	100	241.3	68	31.6	46.18
27	1673	brome				100	492.9	68.1	31.5	

Table A-11. Raw data for brome moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		71.1	38.5	
2		open				50		71.1	38.8	
3		open				100		71.4	39	
4	1185	brome	72.99	93.69	90.91	25	50.1	71.3	38.9	13.43
5	1185	brome				25	99.9	71.2	39.1	
6	1631	brome	76.88	96.83	93.36	50	100	71.4	39.2	17.39
7	1631	brome				50	199.7	71.5	39.1	
8	1646	brome	74.91	99.61	95.07	100	200.1	71.6	38.9	18.38
9	1646	brome				100	400.1	71.5	39	
10		open				25		71.7	39.1	
11		open				50		71.8	39.4	
12		open				100		71.9	39.1	
13	1703	brome	74.12	88.81	86.6	25	50.1	71.8	39	15.04
14	1703	brome				25	100.2	72.1	39.1	
15	1183	brome	76.72	95.55	92.7	50	100.4	72.2	39	15.14
16	1183	brome				50	200.3	72	39.1	
17	1692	brome	75.49	98.96	95.37	100	199.6	72.2	39.1	15.30
18	1692	brome				100	400.2	72.3	38.8	
19		open				25		72.3	38.8	
20		open				50		72.3	38.6	
21		open				100		72.5	38.6	
22	1682	brome	75.82	102.09	97.64	25	50.2	72.1	38.2	16.94
23	1682	brome				25	100.3	72.4	38.4	
24	1643	brome	76.13	100.63	95.71	50	99.9	72.2	38.3	20.08
25	1643	brome				50	200.1	72.5	38.4	
26	1179	brome	73.28	96.27	92.86	100	200.1	72.1	38.3	14.83
27	1179	brome				100	399.8	71.9	38.3	

Table A-12. Raw data for brome moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		69.4	27.4	
2		open				50		68.8	27.5	
3		open				100		68.7	27.4	
4	1697	brome	74.04	92.17	90.57	25	44.9	68.5	27.7	8.83
5	1697	brome				25	90.1	68.5	27.7	
6	1050	brome	75.77	97.5	95.56	50	90.1	68.4	27.6	8.93
7	1050	brome				50	180	68.2	27.6	
8	1174	brome	77.4	96.75	94.97	100	179.8	67.4	27.7	9.20
9	1174	brome				100	359.9	66.1	27.8	
10		open				25		64.9	27.8	
11		open				50		64.2	27.7	
12		open				100		63.2	27.6	
13	1042	brome	74.8	95.42	93.3	25	44.9	62	27.6	10.28
14	1042	brome				25	88.9	61.2	27.6	
15	1024	brome	73.6	92.16	90.51	50	90.1	90.8	27.7	8.89
16	1024	brome				50	180.1	60.5	27.8	
17	1046	brome	75.55	97.77	95.9	100	179.8	60	28	8.42
18	1046	brome				100	360.3	60	29.2	
19		open				25		68.4	24.2	
20		open				50		68.4	24.2	
21		open				100		60.4	28.3	
22	1028	brome	75.14	98.36	96.38	25	45.3	60	28.5	8.53
23	1028	brome				25	90	58.6	29.2	
24	1026	brome	73.94	88.46	87.07	50	88.8	57.5	29.8	9.57
25	1026	brome				50	180	56.8	30.1	
26	1186	brome	75.53	92.35	90.88	100	180.1	56.1	30.2	8.74
27	1186	brome	75.53	92.35	90.88	100	360	55.8	30.3	

Table A-13. Raw data for orchard moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		69.7	69.3	
2		open				50		69.3	40.1	
3		open				100		69.5	37.8	
4	1635	orchard	77.16	126.74	94.98	25	201.8	69.5	36.9	64.06
5	1635	orchard				25	401.6	69.9	35.1	
6	1624	orchard	75.51	137.45	96.04	50	398	70	36	66.86
7	1624	orchard				50	799.7	69.8	35.1	
8	1648	orchard	76.46	144.26	99.81	100	802.8	69.6	34.3	65.56
9	1648	orchard				100	1604.9	69.6	34.9	
10		open				25		69.5	34.2	
11		open				50		69.5	34.7	
12		open				100		69.5	34.3	
13	1625	orchard	75.11	153.79	102.77	25	202.6	69.4	34.6	64.84
14	1625	orchard				25	405.8	69.2	33.6	
15	1634	orchard	77.44	149.28	100.88	50	404.2	69.1	34.2	67.37
16	1634	orchard				50	805	69	35.5	
17	1650	orchard	77.29	159.1	102.34	100	801.2	68.7	34.7	69.38
18	1650	orchard				100	1607.2	68.6	35.5	
19		open				25		68.7	35.1	
20		open				50		68.6	34.6	
21		open				100		68.5	34.3	
22		orchard	75.22	124.46	92.5	25	200.1	68.3	33.5	64.91
23						25	402.8	68.3	33.7	
24		orchard	77.1	134.26	99.19	50	400.2	68.3	33.5	61.35
25		orchard				50	801.9	68.1	33.8	
26		orchard	75.89	145.52	99.08	100	803.7	68	33.4	66.70
27		orchard				100	1602.5	67.9	33.6	

Table A-14. Raw data for orchard moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		67.7	30.5	
2		open				50		67.3	31.2	
3		open				100		67.3	31.3	
4	1176	orchard	74.32	97.18	93.17	25	50	67.4	31.5	17.54
5	1176	orchard				25	99.8	67.3	31.7	
6	1182	orchard	74.61	98.39	91.26	50	100.6	67.4	31.7	29.98
7	1182	orchard				50	200.5	67.5	31.6	
8	1632	orchard	75.8	98.35	93.97	100	200.3	67.7	31.3	19.42
9	1632	orchard				100	400	67.8	31.7	
10		open				25		67.4	31.4	
11		open				50		68.5	31.5	
12		open				100		68.8	31.6	
13	1642	orchard	73.67	96.66	92.54	25	50	70.5	34.9	17.92
14	1642	orchard				25	100.2	70.7	34.9	
15	1184	orchard	74.89	99.86	91.61	50	99.9	71	35.1	33.04
16	1184	orchard				50	199.8	71.2	35.3	
17	1181	orchard	76.56	109.94	102.53	100	199.6	71.4	35.6	22.20
18	1181	orchard				100	399.9	71.6	36	
19		open				25		71.8	36.3	
20		open				50		72.1	36.4	
21		open				100		72.4	36.8	
22	1200	orchard	76.1	93.26	88.91	25	49.9	72.4	37	25.35
23	1200	orchard				25	100.1	72.4	37.3	
24	1647	orchard	76.63	94.54	91.68	50	100.3	71.4	36.7	15.97
25	1647	orchard				50	200	71.7	36.8	
26	1691	orchard	76.62	106.42	96.97	100	200.2	71.5	37.4	31.71
27	1691	orchard				100	399.9	71	37.2	

Table A-15. Raw data for orchard moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		68	32.2	
2		open				50		68.4	31.9	
3		open				100		68.6	32.1	
4	1664	orchard	75.38	100.95	95.24	25	59.2	68.9	32.2	22.33
5	1664	orchard				25	119	69.1	32.3	
6	1677	orchard	75.69	104.22	96.77	50	121.8	68.7	32.3	26.11
7	1677	orchard				50	241.7	68.4	32.7	
8	1675	orchard	74.28	97.64	90.94	100	239.9	68.2	32.7	28.68
9	1675	orchard				100	492.3	67.9	32.7	
10		open				25		67.9	32.5	
11		open				50		67.9	32.5	
12		open				100		67.8	32.5	
13	1653	orchard	75.32	98.67	90.37	25	60.2	67.7	32.4	35.55
14	1653	orchard				25	120.5	67.6	32.4	
15	1661	orchard	77.07	108.12	99.84	50	121.6	67.8	32.4	26.67
16	1661	orchard				50	242.1	67.9	32.4	
17	1674	orchard	76.1	106.96	97.86	100	241.9	68.1	32.2	29.49
18	1674	orchard				100	494	68.5	32.2	
19		open				25		68.7	32	
20		open				50		69	32.5	
21		open				100		69.5	32.9	
22	1662	orchard	74.98	106.45	94.66	25	59.7	70	32.9	37.46
23	1662	orchard				25	122.6	70.2	33.3	
24	1652	orchard	75.03	120.35	104.44	50	121.2	70.2	33.4	35.11
25	1652	orchard				50	241.6	70.3	33.5	
26	1676	orchard	74.78	106	100.61	100	239.6	70.7	33.5	17.26
27	1676	orchard				100	490.1	70.8	33.5	

Table A-16. Raw data for orchard moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		68.6	31.5	
2		open				50		68.6	31.3	
3		open				100		68.6	31.3	
4	1686	orchard	77.26	92.54	91	25	45	68.5	31.2	10.08
5	1686	orchard				25	90	68.6	31	
6	1698	orchard	74.72	98.56	96.23	50	89.7	68.8	31	9.77
7	1698	orchard				50	179.7	69.1	31.2	
8	1699	orchard	75.57	91.16	89.06	100	180.3	69.6	31.2	13.47
9	1699	orchard				100	360	69.8	31.2	
10		open				25		70.1	31.3	
11		open				50		70.1	31.2	
12		open				100		70.2	31.4	
13	1708	orchard	75.27	93.96	90.96	25	44.8	71	31.9	16.05
14	1708	orchard				25	89.7	71.2	32.2	
15	1704	orchard	77.32	91.63	90.16	50	90.3	71.3	32.1	10.27
16	1704	orchard				50	180.5	71.5	32.3	
17	1687	orchard	74.04	92.58	91.17	100	180	71.7	32.4	7.61
18	1687	orchard				100	359.8	71.9	32.3	
19		open				25		71.9	32.7	
20		open				50		72.1	32.7	
21		open				100		72.2	32.6	
22	1706	orchard	75.79	92.27	90.35	25	44.6	72.1	32.6	11.65
23	1706	orchard				25	89.7	71.6	32.7	
24	1690	orchard	73.84	92.33	90.03	50	90.2	71.5	32.8	12.44
25	1690	orchard				50	180.4	71.2	32.8	
26	1695	orchard	77.07	107.3	104.52	100	179.8	71	32.8	9.20
27	1695	orchard				100	359.5	71.1	32.8	

Table A-17. Raw data for brome/alfalfa moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		72.3	39.7	
2		open				50		72.6	40	
3		open				100		72.4	39.4	
4	925	bral	74.93	135.52	91.92	25	201.9	72.6	38.8	71.96
5	925	bral				25	402.6	72.5	39.6	
6	938	bral	73.94	138.15	92.45	50	402.9	72.6	38.9	71.17
7	938	bral				50	803.2	72.4	39.4	
8	940	bral	76.93	138.33	94.65	100	800.5	72.4	38.9	71.14
9	940	bral				100	1600.8	72.3	38.9	
10		open				25		72.2	38.7	
11		open				50		72.1	39.1	
12		open				100		71.9	38.8	
13	960	bral	75	135.3	94.12	25	202.4	71.8	39	68.29
14	960	bral				25	403.2	72	38.7	
15	957	bral	76.87	173.75	107.72	50	402.3	72.1	38.4	68.16
16	957	bral				50	803.7	72.2	38.3	
17	941	bral	76.77	147.97	98.92	100	798.1	72.2	38.4	68.89
18	941	bral				100	1599.5	72.2	38.2	
19		open				25		72.2	38.2	
20		open				50		72.1	38.2	
21		open				100		72	38.2	
22	956	bral	75.97	155.17	98.75	25	202	72	37.7	71.24
23	956	bral				25	404.2	71.9	37.8	
24	934	bral	75.98	155.72	102.9	50	400.1	71.9	38	66.24
25	934	bral				50	803.1	71.8	37.5	
26	952	bral	74.68	155.77	98.33	100	800.8	71.8	37.5	70.83
27	952	bral				100	1598.8	71.6	37.5	

Table A-18. Raw data for brome/alfalfa moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				100		69.7	37.3	
2		open				25		69.7	37.2	
3		open				50		70	37.3	
4	1211	bral	76.32	121.87	106.87	25	60.4	69.8	37.6	32.93
5	1211	bral				25	121	69.9	37.4	
6	1218	bral	76.91	112.93	102.27	50	120.5	70.2	36.9	29.59
7	1218	bral				50	240.8	70.4	37.1	
8	1219	bral	76.51	114.13	99.91	100	240	70.3	36.7	37.80
9	1219	bral				100	480	70.3	36.6	
10		open				25		70.3	36.8	
11		open				50		70.3	36.7	
12		open				100		70.4	36.7	
13	919	bral	76.95	123.55	109.91	25	60.3	70.4	36.3	29.27
14	919	bral				25	121	70.5	37	
15	922	bral	74.52	114.5	103.01	50	119.1	70.3	36.9	28.74
16	922	bral				50	239	70.2	37.1	
17	914	bral	76.54	120.75	100.05	100	240.6	70.1	37.3	46.82
18	914	bral				100	480	70.2	37.4	
19		open				25		70.3	36.6	
20		open				50		70.1	37.1	
21		open				100		70.3	37.1	
22	1209	bral	76.91	126.23	105.6	25	60.1	70.8	36.6	41.83
23	1209	bral				25	119.8	71.1	37.1	
24	901	bral	75.47	96.6	93.11	50	119.9	71.2	36.2	16.52
25	901	bral				50	239.9	71.2	36.7	
26	902	bral	75.63	116.49	103.96	100	240.1	71.2	36.2	30.67
27	902	bral				100	480.4	71.2	36.4	

Table A-19. Raw data for brome/alfalfa moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		70.8	35.8	
2		open				50		71.3	35.6	
3		open				100		71.6	35.3	
4	1023	bral	75.43	88.27	86.53	25	49.7	71.5	35.8	13.55
5	1023	bral				25	100.2	71.6	35.5	
6	1022	bral	72.71	88.3	86.3	50	100	71.7	35.5	12.83
7	1022	bral				50	200.5	71.7	35.5	
8	1036	bral	75.44	100.16	97.03	100	200.6	71.6	35.3	12.66
9	1036	bral				100	699.8	71.5	35.6	
10		open				25		71.6	35.4	
11		open				50		71.6	35.7	
12		open				100		71.6	35.8	
13	1048	bral	74.87	100.25	96.19	25	50.7	71.7	35.5	16.00
14	1048	bral				25	100.4	71.7	35.8	
15	1047	bral	73.25	94.43	90.89	50	98.5	71.7	35.4	16.71
16	1047	bral				50	200.1	71.8	35.3	
17	1049	bral	75.47	91.24	89.28	100	200.3	71.7	35.4	12.43
18	1049	bral				100	400.6	71.7	35.3	
19		open				25		71.7	35.2	
20		open				50		71.8	35.6	
21		open				100		71.7	35.4	
22	1038	bral	74.64	90.6	88.79	25	50.5	71.7	35.3	11.34
23	1038	bral				25	99.9	71.5	35.4	
24	1043	bral	75.81	95.72	93.74	50	100.8	71.8	35.1	9.94
25	1043	bral				50	201.4	71.8	34.8	
26	1033	bral	75.34	96.81	93.74	100	200.2	71.6	34.8	14.30
27	1033	bral				100	400.2	71.7	34.7	

Table A-20. Raw data for brome/alfalfa moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		69.6	39.3	
2		open				50		69.7	39.5	
3		open				100		69.7	39.1	
4	1694	bral	75.35	97.67	95.58	25	45.3	69.7	38.9	9.36
5	1694	bral				25	90.3	69.7	38.9	
6	1688	bral	74.72	92.35	90.43	50	90.2	70	38.9	10.89
7	1688	bral				50	179.9	70	39	
8	1705	bral	74.66	86.67	85.64	100	180.2	70	39.1	8.58
9	1705	bral				100	360	70.2	39.1	
10		open				25		70.1	39.2	
11		open				50		70.2	39	
12		open				100		70.4	39	
13	1710	bral	76.71	91.22	90.12	25	45.2	70.6	38.9	7.58
14	1710	bral				25	90.2	70.6	38.8	
15	1687	bral	74.04	92.58	91.17	50	90.1	70.7	38.6	7.61
16	1687	bral				50	180.2	70.6	38.7	
17	1685	bral	74.74	91.62	90.09	100	180.2	70.8	38.5	9.06
18	1685	bral	74.74	91.62	90.09	100	359.8	70.8	38.8	
19		open				25			38.5	
20		open				50			38.4	
21		open				100			38.3	
22	1696	bral	75.03	93.04	91.54	25	45.2	71.2	38.6	8.33
23	1696	bral				25	90.1	71.2	38.3	
24	1707	bral	76.33	89.49	88.45	50	90.2	71.3	38.3	7.90
25	1707	bral				50	180.4	71.7	38.2	
26	1709	bral	75.95	91.14	89.75	100	179.9	71.8	38.1	9.15
27	1709	bral				100	359.8	71.9	38.4	

Table A-21. Raw data for brome/clover moisture content 4.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		72.5	40.7	
2		open				50		72.3	41.1	
3		open				100		72.7	40.3	
4	928	brcv	74.71	130.7	91.83	25	202.3	72.5	40.6	69.42
5	928	brcv				25	402.7	72.9	40.6	
6	929	brcv	75.46	140.63	98.29	50	401.1	72.3	40.4	64.97
7	929	brcv				50	804.9	72.5	40.3	
8	931	brcv	74.55	172.53	109.32	100	802	72.5	40.4	64.51
9	931	brcv				100	1603.7	72.6	40.5	
10		open				25		72.5	40.3	
11		open				50		72.6	40.4	
12		open				100		72.8	40.3	
13	930	brcv	74.69	134.36	93	25	199.6	72.9	40.3	69.31
14	930	brcv				25	403.5	72.3	40.1	
15	926	brcv	75.76	159.41	102	50	402.8	72.1	40.4	68.63
16	926	brcv				50	803.8	72	40.4	
17	927	brcv	75.92	152.18	100.02	100	801.2	72.1	40.4	68.40
18	927	brcv				100	1603.7	72.1	40.1	
19		open				25		72.3	39.7	
20		open				50		72.6	39.6	
21		open				100		72.7	39.7	
22	932	brcv	74.54	144.12	94.21	25	199.5	72.6	38.9	71.73
23	932	brcv				25	402.5	72.4	39.1	
24	935	brcv	76.17	142.21	98.28	50	397.7	72.5	39.1	66.52
25	935	brcv				50	800.5	72.3	39.3	
26	950	brcv	76.8	174.76	104.3	100	803.3	72.4	38.9	71.93
27	950	brcv				100	1604.3	72.2	39.2	

Table A-22. Raw data for brome/clover moisture content 3.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		70.1	37.9	
2		open				50		70.2	38.3	
3		open				100		70.2	38.7	
4	1226	brcv	74.63	100.2	90.34	25	59.5	70.2	39	38.56
5	1226	brcv				25	120.2	70.3	39.1	
6	1207	brcv	75.19	96.1	88.83	50	120	70.5	39.3	34.77
7	1207	brcv				50	240.2	70.7	39.8	
8	918	brcv	74.1	117.86	96.97	100	239.6	70.5	39.7	47.74
9	918	brcv				100	479.7	70.7	39.5	
10		open				25		70.7	39.5	
11		open				50		70.6	39.5	
12		open				100		70.8	39.8	
13	1215	brcv	75.6	122.73	101.17	25	59.1	71	38.9	45.75
14	1215	brcv				25	119.5	71	38.9	
15	1212	brcv	75.16	98.24	91.11	50	120.4	71.3	39	30.89
16	1212	brcv				50	241.5	71.5	38.4	
17	1214	brcv	75.31	108.23	98.39	100	240.8	70.9	37.9	29.89
18	1214	brcv				100	480.7	70.6	38.1	
19		open				25		70	38.2	
20		open				50		70	37.8	
21		open				100		70	37.8	
22	1210	brcv	76.52	105.43	94.36	25	59.5	69.8	38.1	38.29
23	1210	brcv				25	119.7	69.7	38	
24	1225	brcv	75.26	103.94	94.6	50	120.7	69.7	37.9	32.57
25	1225	brcv				50	240.3	69.5	37.9	
26	1208	brcv	77.03	117.23	103.7	100	239.4	69.5	38.1	33.66
27	1208	brcv				100	480	69.5	37.6	

Table A-23. Raw data for brome/clover moisture content 2.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		68	29.7	
2		open				50		68.1	30.1	
3		open				100		38.3	30.3	
4	1030	brcv	76.07	92.2	89.84	25	50.2	68	32.4	14.63
5	1030	brcv				25	100.5	38.5	32.5	
6	1025	brcv	73.81	94.47	91.19	50	99.8	69.3	33.5	15.88
7	1025	brcv				50	199.9	69.3	33.1	
8	1039	brcv	74.96	99.97	96.93	100	200.6	69.5	33.8	12.16
9	1039	brcv				100	400.5	69.8	34.3	
10		open				25		70	34.6	
11		open				50		70.1	34.4	
12		open				100		70.1	34.4	
13	1034	brcv	76.38	97.34	93.96	25	49.7	70.5	34.9	16.13
14	1034	brcv				25	99.9	70.7	35.1	
15	1040	brcv	73.94	101.23	96.54	50	99.7	71	35.2	17.19
16	1040	brcv				50	200.1	71.2	35.5	
17	1029	brcv	75.14	97.71	94.49	100	200	71.4	35.4	14.27
18	1029	brcv				100	399.9	71.5	35.6	
19		open				25		71.6	35.5	
20		open				50		71.3	35.3	
21		open				100		70.4	35.4	
22	1021	brcv	74.59	90.09	88.18	25	50.1	70.8	35.5	12.32
23	1021	brcv				25	100	70.7	35.7	
24	1027	brcv	74.66	99.4	94.92	50	100.4	70.8	35.7	18.11
25	1027	brcv				50	200.4	70.8	35.6	
26	1045	brcv	74.15	94.55	89.5	100	200.6	70.7	35.7	24.75
27	1045	brcv				100	400.3	70.7	35.7	

Table A-24. Raw data for brome/clover moisture content 1.

Sample ID #	Container #	Material	Container Mass	Wet Material and Container Mass	Dry Material and Container Mass	%Material	Total Mass in Test Fixture	Temperature	Humidity	Moisture Content (Wet Basis)
1		open				25		70	38.4	
2		open				50		69.9	38.5	
3		open				100		69.9	39	
4	1702	brcv	74.33	89.91	88.61	25	45.2	68.9	39.3	8.34
5	1702	brcv				25	89.7	68	40.1	
6	1621	brcv	75.14	105.16	102.53	50	89.9	67.6	39.8	8.76
7	1621	brcv				50	179.9	67.3	40.1	
8	1684	brcv	74.81	100.01	97.82	100	179.9	67.2	39.8	8.69
9	1684	brcv				100	360	67.2	39.7	
10		open				25		67.1	39.6	
11		open				50		67.1	39.6	
12		open				100		67	39.7	
13	1683	brcv	75.69	89.75	88.64	25	45.1	67	39.6	7.89
14	1683	brcv				25	90.3	66.9	39.6	
15	1701	brcv	75.66	100.53	98.52	50	89.8	66.8	39.5	8.08
16	1701	brcv				50	180.3	67.1	39.7	
17	1633	brcv	75.28	101.34	99.05	100	180	67.2	39.8	8.79
18	1633	brcv				100	360	67.1	39.5	
19		open				25		67.8	39.8	
20		open				50		68	39.8	
21		open				100		68.2	40	
22	1681	brcv	74.23	95.57	93.57	25	45.1	68.4	39.4	9.37
23	1681	brcv				25	90.1	68.6	39.5	
24	1693	brcv	75.58	90.13	89.05	50	89.9	69	39.1	7.42
25	1693	brcv				50	180	68.9	39.6	
26	1700	brcv	73.76	89.95	88.71	100	180.6	69	39.3	7.66
27	1700	brcv				100	360.4	69.2	39.3	

REFERENCES CITED

Agricultural Engineers Yearbook of Standards. 1993. S358.2. Moisture measurement-forages. St. Joseph, Mich.: ASAE.

Angelone, A., J. M. Toledo, and J. C. Burns. 1980. Herbage measurement in situ by electronics. 2. Theory and design of an earth-plate capacitance meter for estimating forage dry matter. *Grass Forage Science* 35(2): 95-103.

Čech, V., and L. Poledníček. 1989. A capacitance moisture sensor for forage. *Scientia Agriculturae Bohemoslovaca* 21(2): 149-156.

Jorgensen, J. L., A. R. Edison, S. O. Nelson, and L. E. Stetson. 1970. A bridge method for dielectric measurements of grain and seed in the 50- to 250-MHz range. *Transactions of the ASAE* 13(1): 18-20, 24.

Kandala, C. V. K., R. G. Leffler, S. O. Nelson, and K. C. Lawrence. 1987. Capacitive sensors for measuring single-kernel moisture content in corn. *Transactions of the ASAE* 30(3): 793-797.

Ko, R. S., and G. C. Zoerb. 1970. Dielectric Constant of Wheat Straw. *Transactions of the ASAE* 13(1): 42-45, 47.

Lawrence, K. C., and S. O. Nelson. 1993. Radio-frequent density-independent moisture determination in wheat. *Transactions of the ASAE* 36(2): 477-483.

Lawrence, K. C., S. O. Nelson, and P. G. Bartley, Jr. 1998. Measuring dielectric properties of hard red winter wheat from 1 to 250 MHz with a Flow-through coaxial sample holder. *Transactions of the ASAE* 41(1): 143-150.

Nelson, S. O. 1976. Microwave dielectric properties of insects and grain kernels. *Journal of Microwave Power* 11(4): 299-303.

Nelson, S.O. 1982. Factors affecting the dielectric properties of grain. *Transactions of the ASAE* 25(4): 1045-1049, 1056.

Nelson, S. O., L. H. Soderholm, and F. D. Yung. 1953. Determining the dielectric properties of grain. *Agricultural Engineering* 34(9): 608-610.

Nelson, S. O., and W.W. Wolf. 1964. Reducing hard seed in alfalfa by radio-frequency electrical seed treatment. *Transactions of the ASAE* 7(2): 116-119, 122.

Stetson, L. E., S. O. Nelson. 1970. A method for determining dielectric properties of grain and seed in the 200- to 500-MHz range. *Transactions of the ASAE* 13(4): 491-495.

Stetson, L. E., S. O. Nelson. 1972. Audio-frequency dielectric properties of grain and seed. *Transactions of the ASAE* 15(1): 180-184, 188.

Stenning, B. C., and P. A. Berbert. 1993. On line moisture content measurement. *Aspects of Applied Biology Cereal Quality III* 36: 443-456.

Trabelsi, S., A. W. Kraszewski, and S. O. Nelson. July 18-21, 1999. Arlington VA. Density-independent permittivity functions for moisture sensing in foods and agricultural products. *International Microwave Power Institute 34th Annual Microwave Power Symposium Proceedings*, pp. 9-12.

Zoerb, G. C., G. A. Moore, and R. P. Burrow. 1993. Continuous measurement of grain moisture content during harvest. *Transactions of the ASAE* 36(1): 5-9.

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